DETERMINING MARINE PARTICULATE AND DISSOLVED MATERIAL PROPERTIES FROM MEASUREMENTS OF THEIR INHERENT OPTICAL PROPERTIES IN SITU

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Abstract
DETERMINING MARINE PARTICULATE AND DISSOLVED MATERIAL PROPERTIES FROM MEASUREMENTS OF THEIR INHERENT OPTICAL PROPERTIES IN SITU

by Eufemia Palomino

Particle and dissolved absorption, $a_p$ and $a_y$, and particle scattering, $b_p$, coefficients were determined using an AC-9 and particle backscattering, $b_{bp}$, coefficients were measured with a HydroScat-6, along a section of the central California coast. The composition (whether living algal cells, detritus, or dissolved material), relative concentration of particulate and dissolved material and relative particle size distribution were determined from optical profiles within and below the mixed layer in coastal waters and within and below the mixed layer in oceanic waters. Within the coastal mixed layer, the dominant constituent was living algal cells as evidenced by a strong chlorophyll spectrum, a high $a_p:a_y$ ratio (66:34, n=5, s=10.0), and a system dominated by larger particles ($b_{bp}/b_p(488 \text{ nm}) = 0.01$ and $\gamma = 0.5$ (gamma, $\gamma$, is the slope relating the backscattering coefficient to the wavelength). Below the coastal mixed layer, detritus and dissolved material became more important: $a_p:a_y$ ratio was relatively lower (45:55, n=5, s=9.3) and the system was dominated by smaller particles ($b_{bp}/b_p(488 \text{ nm}) = 0.03$ and $\gamma = [1-1.3]$). In oceanic waters, constituents were equally comprised of living algal cells and dissolved material ($a_p:a_y = 55:45$) and the system was dominated by smaller particles ($\gamma = 1.3$). Below the oceanic mixed layer dissolved and detritus became more important once passed the subsurface chlorophyll maximum.
Acknowledgements

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Introduction

A variety of methods and techniques have been used to study the size distribution, concentration, and composition of the phytoplankton, detritus and dissolved material in the ocean. Usually, these methods utilize discrete water sampling (Bricaud et al. 1981; Kishino et al. 1985; Li and Wood 1988). However, with the advent of an in situ multi-spectral (nine $\lambda$’s) absorption and attenuation meter (AC-9) (Zaneveld et al. 1988, 1992) and an in situ multi-spectral (six $\lambda$’s) backscattering meter (HydroScat-6) (Maffione and Dana 1997) the size distribution, concentration and composition of constituents in the ocean can be inferred in almost real time at high depth resolution. Although absorption and scattering coefficients are not direct measurements of the concentration, particle size distribution or composition of suspended particles (usually living algal cells or detritus) and dissolved material, analysis of the optical coefficients and the shape of their spectra allow us to infer the distribution and properties of these materials with a much higher vertical resolution and in real time. As with all methods, this method has disadvantages including a low spectral resolution and a somewhat demanding calibration and deployment process.

The objective of this research was to use in situ absorption, $a(\lambda)$, scattering, $b(\lambda)$, and backscattering, $b_b(\lambda)$, coefficients to infer the size distribution, concentration and composition of the particulate and dissolved material along CalCOFI (California Cooperative Oceanic Fisheries Investigation) transect 67 in May 1999. A second objective was to analyze the differences in the size distribution, concentration and
composition of particles and dissolved material between the coastal and oceanic waters along CalCOFI transect 67.

These properties were observed along a transect from the Monterey Bay area extending through the California Current system during the upwelling season. The California Current system is characterized by complex flow patterns dominated by southward mesoscale eddies (Wooster and Reid 1963; Wyllie 1966) and is strongly influenced by coastal upwelling. The upwelling season, falling between February and September, occurs when equatorward, along-shore winds act in combination with the Coriolis force to move surface waters offshore bringing deeper, colder, nutrient-rich waters into the euphotic zone along the coast (Barber and Smith 1981; Huyer 1983; Lynn and Simpson 1987; Hutchings et al. 1995). The transect can be divided into three zones based on temperature, seawater density, and chlorophyll concentrations. The coastal region is defined by a dense, cool band of ‘upwelled’ water occurring along the coast, which is typically several tens of kilometers broad (Kelly 1985; Strub et al. 1991). The transition zone, typically between 60 – 150 km from the coast, is characterized by a series of fronts, plumes and eddies (Kosro et al. 1991; Strub et al. 1991). The oceanic zone, which is not a part of the California Current system, is characterized by warm, less dense waters (Hood et al. 1990; Kosro et al. 1991).

Four areas along the transect in which a comparison was made between in situ optical coefficients and water sampling were in coastal waters within and below the mixed layer and in oceanic waters within and below the mixed layer. The unique characteristics of each of these areas allowed a comparison to be made between the two
methods within each zone. In the coastal zone, nutrient-rich waters from below the mixed layer upwell into the mixed layer and support high levels of phytoplankton and a greater energy transfer to higher trophic levels (Barber and Smith 1981; Chavez et al. 1991; Hutchings et al. 1995). Therefore, the dominant constituent within the mixed layer in the coastal zone was expected to be due to living algal cells consisting, for the most part, of large diatoms (Garrison 1979). In contrast, below the coastal mixed layer, the dominant constituent was expected to be due to relatively small detrital particles and perhaps partially due to dissolved material. In the oceanic zone, waters are nutrient-poor, have lower chlorophyll concentrations and smaller particles. Therefore, we expected oceanic mixed layers to be dominated by very small living algal cells and the area below the oceanic mixed layer to be dominated by detrital and dissolved material.
Background

According to Preisendorfer (1961, 1976) the inherent optical properties (IOPs) consist of the absorption, scattering, and attenuation coefficients, a, b, and c, with

\[ c(\lambda) = a(\lambda) + b(\lambda) \quad (\text{m}^{-1}) \]  

and the volume scattering function, \( \beta(\theta) \). The wavelength symbol in parentheses, (\( \lambda \)), shows that these optical quantities are spectrally dependent.

Inherent optical properties, (IOPs), are a function only of the constituents of the water, either particulate or dissolved, or of the water itself and the additivity principle applies strictly to these properties. Apparent optical properties, such as the diffuse attenuation coefficient (\( K_d \)), (AOPs: Preisendorfer 1961, 1976), are dependent on inherent optical properties and boundary conditions such as, surface waves and sun altitude, that affect the ambient light field in the ocean.

Because the IOPs directly correlate with properties of the water, they are important to study if we are interested in knowing about the composition, concentration and size distribution of the water’s constituents. The optical properties of natural waters differ from that of pure water because of variable amounts of diverse dissolved and particulate substances. From an optical point of view, these substances can be considered as belonging to four groups: living algal cells; detritus derived from these algae; mineral particles and resuspended sediment; and dissolved organic (yellow) substances (Bricaud et al. 1983).
The following provides background on how absorption and scattering properties are used to infer the composition, concentration and particle size distribution of these four constituents.

**Absorption** – The total absorption coefficient can be represented as the sum of the absorption due to water \(a_w\), due to phytoplankton \(a_{ph}\), due to detrital material from marine or terrestrial origin \(a_d\), and due to dissolved matter (also known as yellow substances) \(a_y\) (Prieur and Sathyendranath 1981; Roesler et al. 1989):

\[
a_T(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_d(\lambda) + a_y(\lambda). \quad (m^{-1}) \tag{2}
\]

Absorption due to water, \(a_w(\lambda)\), may be considered to be constant, although it is very difficult to measure the true value due to the difficulty of removing all impurities. The values given by Pope and Fry (1988) of the spectral absorption coefficient of pure water (Fig. 1) will be used for this study (Table 1).

The components of absorption due to particles, \(a_p(\lambda)\), can be divided into absorption due to phytoplankton, \(a_{ph}(\lambda)\), and absorption due to detritus, \(a_d(\lambda)\).

\[
a_p(\lambda) = a_{ph}(\lambda) + a_d(\lambda) \quad (m^{-1}) \tag{3}
\]

Several approaches have been developed to obtain estimates of absorption due to phytoplankton separated from detritus. One approach is to filter total particulates from a water sample (Yentsch 1962; Kiefer and SooHoo 1982; Mitchell and Kiefer 1984, 1988) and then separate the phytoplankton from the detrital component chemically (Kishino et al. 1985). The latter method is the method used in this study. With this method there is no distinction made between detritus from organic origin and suspended sediments. The absorption spectra of the separated components, phytoplankton and detritus, can be
Fig. 1 Absorption coefficient due to pure water (Pope and Fry 1988). Redrawn using coefficients from their Table 3.
Table 1. Pure water coefficients for absorption and attenuation for the AC-9.

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>$a_w$ (m$^{-1}$)$^\dagger$</th>
<th>$c_w$ (m$^{-1}$)$^\ddagger$</th>
</tr>
</thead>
<tbody>
<tr>
<td>412</td>
<td>0.004562</td>
<td>0.009662</td>
</tr>
<tr>
<td>440</td>
<td>0.00635</td>
<td>0.01025</td>
</tr>
<tr>
<td>488</td>
<td>0.0146</td>
<td>0.0171</td>
</tr>
<tr>
<td>510</td>
<td>0.325</td>
<td>0.0345</td>
</tr>
<tr>
<td>532</td>
<td>0.4444</td>
<td>0.04614</td>
</tr>
<tr>
<td>555</td>
<td>0.596</td>
<td>0.061</td>
</tr>
<tr>
<td>650</td>
<td>0.34</td>
<td>0.34071</td>
</tr>
<tr>
<td>676</td>
<td>0.4558</td>
<td>0.45641</td>
</tr>
</tbody>
</table>

$^\dagger$ (Pope and Fry 1997)

$^\ddagger$ (Morel 1974)
Fig. 2 The dominant component of absorbing particles can be identified from the shape of the particle absorption, $a_p$, spectrum and the location of its peak. Absorbing particles mainly composed of phytoplankton, as in this example, would have its peak at 443 nm and a secondary peak at 676 nm like the phytoplankton absorption spectrum, $a_{ph}$ (green line). Absorbing particles mainly composed of detritus or suspended sediment would resemble the detrital absorption spectrum, $a_d$ (red line).
distinguished by their shape (Fig. 2). Phytoplankton absorb more strongly at 443 nm
(Bricaud et al. 1983) whereas detritus absorbs more strongly at shorter wavelengths
(Kishino et al. 1985; Roesler et al. 1989). The shape of the particle absorption spectrum
and the location of its peak can give an indication as to whether the composition of the
particles are dominated by phytoplankton or detritus.

Colored dissolved organic matter (CDOM) (also yellow substance, ‘y. s.’) absorbs
light at an exponentially decreasing function of wavelength (Bricaud et al. 1981; Kiefer
and SooHoo 1982; Kirk 1976, 1980, 1983; Roesler et al. 1989) (Fig. 3).

\[ a_y(\lambda) = a_y(\lambda_o)e^{-S(\lambda-\lambda_o)} \]  \hspace{1cm} (4)

The ‘y’ in the dissolved absorption coefficient, \(a_y(\lambda)\), stands for ‘yellow substance’. The
dissolved absorption coefficient, between 400-440 nm, tends to be low in oceanic regions
or in those not influenced by freshwater and higher in coastal regions especially those
influenced by river discharge (Bricaud et al. 1981). The molecular composition of
CDOM changes with time due to proposed processes such as degradation, bacterial
consumption, and photo-oxidation (Williams and Druffel 1988; Blough and Zepp 1990).
The S value, the slope of the log-linear relationship between the dissolved absorption
coefficient and its respective wavelength (Equation 4), can change when the molecular
composition of the CDOM changes.

**Scattering** – The volume scattering function, \(\beta(\theta,\lambda)\), is an inherent optical
property that describes the probability a given photon will travel in a certain direction
(Preisendorfer 1961, 1976). The symbol, \(\beta(\theta,\lambda)\), denotes the volume scattering function
where \(\theta\) is the angle of scattering and \(\lambda\) is the wavelength and it has units of per meter per
Fig. 3  Example of a model of spectral absorption by yellow matter taken from Bricaud, et al. (1981) ($a_y(\lambda) = a_y(\lambda_0) e^{-S(\lambda-\lambda_0)}$).
steradian, m\(^{-1}\) sr\(^{-1}\). Scattering, in natural waters, is symmetric about the photon’s incident direction. Therefore, the azimuthal angle, \(\theta\), is the only variable in angle. Because the volume scattering function is very difficult to measure, the scattering coefficient, \(b(\lambda)\), is used more often. The scattering coefficient is defined as the integral of \(\beta\) over all angles (\(\theta\)).

\[
b(\lambda) = 2\pi \int_0^\pi \beta(\theta, \lambda) \sin \theta d\theta \quad (m^{-1})
\]  

(5)

The scattering coefficient, \(b(\lambda)\), is a parameter which contains the amount of photons scattered in all directions and is given in units of per meter, m\(^{-1}\). It can be divided into forward and backward scattering. The forward scattering coefficient, \(b_f(\lambda)\) is the amount of scattering occurring in the forward hemisphere, from 0 to \(\pi/2\) radians of \(\theta\).

\[
b_f(\lambda) = 2\pi \int_0^{\pi/2} \beta(\theta, \lambda) \sin \theta d\theta \quad (m^{-1})
\]  

(6)

The backward scattering coefficient, \(b_b(\lambda)\) is the amount of scattering occurring in the backward hemisphere, from \(\pi/2\) to \(\pi\) radians of \(\theta\).

\[
b_b(\lambda) = 2\pi \int_{\pi/2}^\pi \beta(\theta, \lambda) \sin \theta d\theta \quad (m^{-1})
\]  

(7)

The total scattering coefficient, \(b_T(\lambda)\), can be separated into the sum of the scattering due to water, \(b_w(\lambda)\), and due to particles, \(b_p(\lambda)\).

\[
b_T(\lambda) = b_w(\lambda) + b_p(\lambda) \quad (m^{-1})
\]  

(8)

Pure water scatters through a process called Einstein-Smoluchowski scattering where small density fluctuations from random molecular motions change the index of refraction. This type of scattering is significant when the particle in question is much
smaller than the wavelength of the incident photon. Therefore, in the ocean, it applies mostly to the water and its associated ions. Morel (1974) found the wavelength dependence in pure seawater to be $\lambda^{-4.32}$ (Equation 9) and these values are used in this study (Table 1).

$$b_w(\lambda) = 16.06 \left( \frac{\lambda_o}{\lambda} \right)^{4.32} \beta_w(90^\circ, \lambda_o) \quad (9)$$

In waters with suspended particles in it, particulate scattering, $b_p$, dominates the scattering coefficient, even in the clearest of oceanic waters. The magnitude of the particle scattering coefficient, $b_p(\bar{c})$, is proportional to the concentration of particles in a system, and will be used in this study as an indicator of relative change in particle concentration. The wavelength dependence of scattering changes from equation 9 when particles are added to pure seawater according to the particle size distribution of the particles. The particle size distribution describes the concentration of particles relative to their size. For example, in the open ocean the particle size distribution is dominated by smaller phytoplankton. Small picoplankton (~1 \(\mu\)m) are 6 orders of magnitudes more abundant than microplankton (~100 \(\mu\)m) microplankton (Stramski and Kiefer 1991) (Fig. 4). In oceanic waters, there is a steep slope between concentration and particle size. However, in coastal areas and in phytoplankton blooms, where larger phytoplankton (i.e., diatoms) are more abundant than in the open ocean the slope of the particle size distribution decreases. The particle size distribution, $n(x)$, is the number of particles per unit volume in the size interval from $x$ to $x + dx$ and has units of inverse meters to the fourth power, m$^{-4}$. 
Fig. 4  Particle size distribution for the open ocean (adapted from Stramski and Kiefer 1991).
The slope of log($n(x)$) vs. log($x$) is $-m$ and $K$ is the y-intercept where $x$ equals some reference size, $x_o$ ($x_o \neq 0$). Oceanic particle size distributions usually have $m$ values between 2 and 5, with $m = 3$ and 4 being typical (McCave, 1983; Stramski and Kiefer 1991; Jackson et al. 1996). Stramski and Kiefer’s figure of particle size distribution (Fig. 4) in the open ocean gives a typical value of $m = 4$.

Particle size distribution will be analyzed using inherent optical properties in two ways. One way uses the slope of the relationship between the particulate backscattering coefficient, $b_{bp}(\lambda)$, and wavelength as an indicator of how the particle size distribution changes. The relationship between the particle backscattering coefficient and wavelength is expressed by equation 11.

\[
 b_{bp}(\lambda) = b_{bp}(\lambda_o)(\lambda/\lambda_o)^\gamma 
\]  
\[
 (m^{-1}) \quad (11)
\]

Gamma, $\gamma$, is the resulting slope of this power law equation. The reference wavelength, $\lambda_o$, can be any wavelength in the visible and the particle backscattering coefficient, $b_{bp}(\lambda)$, by definition has the scattering due to water, $b_w(\lambda)$, subtracted from it (Equation 12).

\[
 b_{bp}(\lambda) = b_b(\lambda) - b_{bw}(\lambda) 
\]  
\[
 (m^{-1}) \quad (12)
\]

Due to the range of index of refraction for organic and inorganic particles naturally occurring in the ocean, the exponential coefficient, gamma, can range between 0 and 2 in the ocean (Maffione and Dana 1997). Values of about 0.5 and less are generally due to a system dominated by larger particles or living organic particles.
Values of about 1.5 and more are generally due to smaller phytoplankton dominating and inorganic/detrital material. Size has a greater affect on gamma than does composition.

Another way of looking at particle size distribution is by looking at the backscattering probability ratio, \( b_{bp}/b_p \). The backscattering probability ratio is the probability that a photon will be scattered in the backward direction (\(90^\circ-180^\circ\)). The complement, the forward scattering ratio, \( b_{fp}/b_p \), also exists for scattering in the forward direction (\(0^\circ-90^\circ\)). To understand how the backscattering probability ratio is an indication of the particle size distribution one must understand how different particle sizes scatter light. When there are no particles in the water, such as in pure water, \( b_f/b = 0.5 \), that is the ratios of forward and backward scattering equal 0.5 (Fig. 5).

When particles are present, however, the forward scattering coefficient increases dramatically and the slope of the phase function is steeply sloped in the forward direction and \( b_{bp}/b_p \) decreases greatly from 0.5 (Fig. 6).

If the slope of the particle size distribution, m, is small, such as in a coastal diatom bloom, then the backscattering probability ratio, \( b_{bp}/b_p \), is low. A coastal region backscattering probability ratio taken from Petzold (1972) was \( b_{bp}/b_p = 0.013 (\lambda = 514 \text{ nm}) \). If the slope of the particle size distribution is large, such as in the open ocean, then the backscattering probability ratio is higher. An oceanic backscattering probability ratio was reported to be \( b_{bp}/b_p = 0.044 (\text{m}^{-1}) (\lambda = 514 \text{ nm}) \) (Petzold 1972). The backscattering probability ratio increases as particle concentration increases and as the slope of the
Fig. 5 The volume scattering function (β) for pure water is symmetrical about 90° (Morel 1974). The backscattering probability ratio, $b_{bp}/b_p = 0.5$ when no particles are present.
Fig. 6  Highly peaked forward scattering, $b_t$, is characteristic of a system containing particles of many different sizes (data from Petzold 1972). The backscattering probability ratio, $b_{bp}/b_p$, decreases dramatically.
particle size distribution increases. Changes in the $b_{sp}/b_p$ ratio due to changes in the index of refraction are negligible (Maffione and Dana 1997).

In summary, the more conventional method (discrete water sampling) and in situ inherent optical properties can both be used to infer the concentration, composition and size distribution of particles and dissolved material and their results compared successfully. For example, the concentration of absorbing particles can be estimated using three quantities: chlorophyll concentration, mg/m$^3$, fluorescence profiles, volts, and particle absorption coefficient, m$^{-1}$, profiles. Second, the qualitative distinction between two major material types (dissolved materials (<0.2 µm) and particulate materials) is inferred. Particles can be further divided among living or detrital particles. Separation of dissolved material from ‘everything else’ is done through filtration either of discrete water samples or in situ. The change in the composition of dissolved material is observed by the change in the $S$ value (Equation 4). Separation of particle absorption coefficients into detrital and phytoplankton components is done with discrete water samples through a methanol extraction method (Kishino et al. 1985). Separation is not possible in situ with the AC-9, however the shape of the particle absorption spectra can indicate the dominant constituent. Particle size distribution is determined with discrete water samples through quantitative phytoplankton counts using epifluorescence microscopy and flow cytometry. When using IOPs the PSD is inferred from the backscattering probability ratio and the relationship between the particle backscattering coefficient and the wavelength (gamma value).
Methods

Sampling

During upwelling season, 22-28 May 1999, an optical profiling platform known as a SlowDROP (Slow Descent Rate Optical Platform) measured spectral absorption and scattering properties of a section of the California Current off of the central coast (Fig. 7). Profiling stations were located along the California Cooperative Oceanic Fisheries Investigation (CalCOFI) transect line 67 which originated at Moss Landing in Monterey Bay, California and went offshore more than 300 km. Discrete water samples and hydrographic data were collected using a CTD/rosette profiler for comparison with the optical profiles.

CTD/Rosette Profiler – A CTD/rosette profiler equipped with Niskin bottles collected hydrographic profiles synoptically with discrete water samples at eleven nominal depths (0, 5, 10, 20, 30, 40, 60, 80, 100, 150, 200 m). Water samples, to determine algal biomass, were taken from these depths at every CTD cast. Eleven CTD casts were made on the transect, including the five stations where the optical profiler was used (Fig. 7 and Table 2).

Chlorophyll concentrations were determined using 90% acetone extraction and standard fluorometric techniques. Particle absorption, \( a_p(\lambda) \), spectra were determined using the filter pad technique developed by Kishino (1985) with a Labsphere RSA-HP-84 integrating sphere mounted on a HP 8452A spectrophotometer. Particle absorption spectra were determined at the surface only with the exception of station ‘M1’, where spectra were determined at 10, 20, and 40 m.
Fig. 7 Station locations for CTD and SlowDROP on CalCOFI transect 67.
Table 2. Position and time of CTD casts on CalCOFI transect 67.

<table>
<thead>
<tr>
<th>Station</th>
<th>GMT</th>
<th>Latitude °N</th>
<th>Longitude °W</th>
<th>Depth of Cast (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>67-90</td>
<td>5/25/99 07:03</td>
<td>35° 27.10’</td>
<td>124° 53.60’</td>
<td>196</td>
</tr>
<tr>
<td>67-85</td>
<td>5/25/99 11:02</td>
<td>35° 39.63’</td>
<td>124° 33.43’</td>
<td>200</td>
</tr>
<tr>
<td>67-80</td>
<td>5/25/99 16:55</td>
<td>35° 47.43’</td>
<td>124° 12.04’</td>
<td>197</td>
</tr>
<tr>
<td>67-75</td>
<td>5/25/99 22:49</td>
<td>35° 57.84’</td>
<td>123° 51.26’</td>
<td>200</td>
</tr>
<tr>
<td>67-70</td>
<td>5/26/99 04:04</td>
<td>36° 07.13’</td>
<td>123° 28.82’</td>
<td>983</td>
</tr>
<tr>
<td>67-65</td>
<td>5/26/99 11:59</td>
<td>36° 18.72’</td>
<td>123° 08.65’</td>
<td>200</td>
</tr>
<tr>
<td>67-60</td>
<td>5/26/99 19:15</td>
<td>36° 27.49’</td>
<td>122° 46.36’</td>
<td>196</td>
</tr>
<tr>
<td>M3</td>
<td>5/26/99 23:52</td>
<td>36° 33.88’</td>
<td>122° 56.11’</td>
<td>192</td>
</tr>
<tr>
<td>M2</td>
<td>5/27/99 06:59</td>
<td>36° 42.10’</td>
<td>122° 26.18’</td>
<td>199</td>
</tr>
<tr>
<td>M1</td>
<td>5/27/99 15:56</td>
<td>36° 43.12’</td>
<td>122° 01.39’</td>
<td>193</td>
</tr>
<tr>
<td>C1</td>
<td>5/27/99 19:26</td>
<td>36° 47.81’</td>
<td>121° 51.13’</td>
<td>200</td>
</tr>
</tbody>
</table>
The particle size distributions for each station were analyzed using two different methods. First, quantitative phytoplankton counts were determined from surface water samples at stations C1, M1 and M3 using epifluorescence microscopy. Epifluorescence microscopy primarily focuses on larger phytoplankton diameters (2 - 50 µm) (Li and Wood 1988). The second method used flow cytometry counts determined at all optical stations and at all depths. For the flow cytometry counts the following diameters were chosen to represent the three size groups: heterotrophic bacteria (0.4 µm), *Synechococcus* (0.75 µm), and pico-eukaryotes (1.0 µm). A fourth group used for station 67-90 included *Prochlorococcus* (0.75 µm) (Olson et al. 1990a, 1990b).

The slope of the particle size distribution slope was determined for stations C1, M1 and M3 at 0 m, using both epifluorescence microscopy and flow cytometry. Then the slope of the particle size distribution was determined again using only the flow cytometer data at multiple depths for eight stations including the optical casts. The slopes were obtained by a log-log regression between the particle diameter and the counts within that size range (Equation 11).

*Optical Profiler* – Five optical profiles were made with the SlowDROP (Slow Descent Rate Optical Platform) on the CalCOFI transect 67 (Fig. 7). At each station sky conditions, and wind speeds were noted (Table 3). Three instruments mounted on the optical profiling system acquired *in situ* measurements of inherent optical properties (IOPs). Spectrally matched absorption, a(λ), and beam attenuation, c(λ), coefficients were measured by two separate AC-9’s (Zaneveld 1988, 1992) and backscattering, b_b(λ), coefficients were measured with a HydroScat-6 (Maffione and Dana 1997).
The two AC-9’s measured absorption, $a(\lambda)$, and attenuation, $c(\lambda)$, over nine wavebands ($\Delta\lambda = 10$ nm) centered on the following wavelengths (412, 442, 488, 510, 532, 555, 650, 676, 715). One AC-9, AC9-1, measured absorption, $a_{py}(\lambda)$, and beam attenuation, $c_{py}(\lambda)$, coefficients due to particulate and dissolved materials. The subscript ‘py’ stands for particles and yellow substance. The other AC-9, AC9-2, was fitted with a 0.2 µm particle filter at the intake of the absorption tube (Fig. 8). This AC-9 only measured the absorption due to dissolved materials, $a_y(\lambda)$.

The backscattering coefficients, $b_b(\lambda)$, from the HydroScat-6 are centered on six 10 nm wavebands (442, 488, 532, 555, 620, 676 nm). Calibration and processing for the AC-9’s and the HydroScat-6 are addressed in the next section.

Additional instruments mounted on the SlowDROP included a Seabird 25 CTD, which measured conductivity, temperature and depth, a WetStar fluorometer, which measured relative fluorescence emission at 685 nm and a data acquisition unit allowed the data from various instruments to be merged based on time (see Table 4 for a listing of instruments on the optical profiler).

The SlowDROP vertical profiling system was configured to provide high (~4 cm) resolution of several physical and bio-optical parameters. The profiler was equipped with several floats to provide near-neutral buoyancy during free-fall profiling. Thus, the SlowDROP profiler sank slowly, approximately 10-20 cm/s. All of the intakes or sensors for the instruments included with the SlowDROP were located at the base of the profiler.
Table 3. Station position, times and weather conditions for SlowDROP casts.

<table>
<thead>
<tr>
<th>Station</th>
<th>Cast</th>
<th>Weather Conditions</th>
<th>GMT</th>
<th>Latitude °N</th>
<th>Longitude °W</th>
<th>Cast Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>67-90</td>
<td>01</td>
<td>Calm, light wind, overcast</td>
<td>05/25/99 2:45</td>
<td>35° 26.82’</td>
<td>124° 53.61’</td>
<td>175</td>
</tr>
<tr>
<td>67-80</td>
<td>01</td>
<td>Overcast, 10ft swell, some whitecaps, wind 10m/s</td>
<td>05/25/99 18:20</td>
<td>35° 48.03’</td>
<td>124° 12.32’</td>
<td>8</td>
</tr>
<tr>
<td>67-80</td>
<td>02</td>
<td>Overcast, wind 10m/s, no whitecaps, 5ft swell</td>
<td>05/25/99 18:30</td>
<td>35° 47.67’</td>
<td>124° 12.20’</td>
<td>104</td>
</tr>
<tr>
<td>M3</td>
<td>01</td>
<td>Overcast, wind 5m/s, no whitecaps, 5ft swell</td>
<td>05/26/99 22:06</td>
<td>36° 33.26’</td>
<td>122° 55.24’</td>
<td>171</td>
</tr>
<tr>
<td>M1</td>
<td>01</td>
<td>Wind 3.5m/s, overcast, calm</td>
<td>05/27/99 16:30</td>
<td>36° 43.23’</td>
<td>122° 01.44’</td>
<td>162</td>
</tr>
<tr>
<td>C1</td>
<td>01</td>
<td>Wind 5m/s, still calm and overcast</td>
<td>05/27/99 22:30</td>
<td>36° 47.40’</td>
<td>121° 51.29’</td>
<td>95</td>
</tr>
</tbody>
</table>
Stainless steel filters
(Rejects particles > 1 mm)

Fig. 8 Schematic diagram of the two AC-9’s mounted on the optical profiling system SlowDROP (adapted from WetLabs AC-9 protocol). A) AC9-1 measures absorption, $a_{py}(\lambda)$, and beam attenuation, $c_{py}(\lambda)$, coefficients (‘py’ = due to particulate and dissolved materials). B) AC9-2 measures the absorption coefficient, $a_{y}(\lambda)$, (‘y’ = due to dissolved materials).
Table 4. Instruments mounted on the SlowDROP

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Company</th>
<th>Parameters</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-9</td>
<td>WetLabs</td>
<td>Absorption and attenuation due to particles and dissolved</td>
<td>( a_{py}, c_{py} )</td>
</tr>
<tr>
<td>AC-9</td>
<td>WetLabs</td>
<td>Absorption due to dissolved only</td>
<td>( a_y )</td>
</tr>
<tr>
<td>HS-6</td>
<td>HOBI Labs</td>
<td>Backscattering</td>
<td>( b_b )</td>
</tr>
<tr>
<td>CTD</td>
<td>Seabird</td>
<td>Salinity, temperature, depth, density</td>
<td>( \text{psu, T, z, } \sigma_t )</td>
</tr>
<tr>
<td>WETStar</td>
<td>WetLabs</td>
<td>Chlorophyll fluorescence</td>
<td></td>
</tr>
<tr>
<td>fluorometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modaps</td>
<td>WetLabs</td>
<td>Data collection archiving unit provided timestamp for individual instruments.</td>
<td></td>
</tr>
</tbody>
</table>
Calibration and Processing

*AC-9* – The AC-9 data needed several calibration checks and corrections before used in analysis. First, calibration coefficients supplied by WetLabs were applied to the AC-9’s. Also, during the cruise, daily pure water calibrations detected drifting within each instrument. Drifting was detected by monitoring the change in the signal produced by a Barnstead Nanopure water system run through the AC-9’s (Fig. 9).

In addition to daily pure water calibrations, which monitored intra-instrument drift, two diagnostic casts monitored inter-instrument drifting. First, the dissolved absorption coefficient, $a_y(\lambda)$, was measured on the absorption sides of the two AC-9’s by attaching 0.2 µm filters. Then both attenuation sides measured dissolved absorption, $a_y(\lambda)$. Because there is no appreciable scattering due to dissolved material ($b_y(\lambda) = 0$) in the attenuation tubes, all four tubes (2 absorption and 2 attenuation tubes) should respond the same to the filtered water.

Daily pure water calibrations did not significantly drift ($< \pm 0.005 \text{ m}^{-1}$) (Twardowski et al. 1999). Also, the diagnostic casts did not demonstrate appreciable differences between instruments. Therefore, only factory calibrations for the AC-9’s were used to correct values.
Fig. 9 Daily pure water calibration of the two AC-9s. AC9-1 measured $a_{py}(\lambda)$ and AC9-2 measured $a_{s}(\lambda)$. No significant drifting occurred during the cruise ($> \pm 0.005$ m$^{-1}$) (Twardowski et al. 1999).
After calibration coefficients were applied, the dissolved absorption, \(a_y(\lambda)\), data were lagged by 20 scans (scan rate = 6 Hz) to compensate for the decreasing flow rate of the water pumped through a 0.2 \(\mu\)m filter. The dissolved absorption, \(a_y(\lambda)\), data were also smoothed. Temperature and salinity corrections were made, using a calibration temperature of 25.5\(^\circ\)C (Pegau, Gray, and Zaneveld 1997), to account for small differences between the pure water absorption coefficient and the in water absorption coefficient (not including its constituents). Finally, the scattering correction was applied to the AC-9 data.

The scattering correction is necessary because the transmitted flux detector at the end of the absorption tube measures the transmitted light plus an unknown portion of the scattered light (Fig. 10). A scattering correction accounts for the amount of scattered light that was not collected at the end of the tube and subtracts it from the measured absorption coefficient to determine the corrected absorption coefficient. Without a scattering correction the measured absorption coefficient \((a_m)\) (Equation 13, Fig. 10) would be overestimated.

\[
a_m = \frac{\ln \left( \frac{\Phi_i}{\Phi_i + f\Phi_s} \right)}{z}
\]  

(13)

The scattering correction is difficult to determine because an unknown portion of the scattered light is not collected and the shape of the volume scattering function may change \textit{in situ} with space and time. In the AC-9 the absorption tube is lined with a quartz tube that reflects light with an incident angle of smaller that 42\(^\circ\) into the path of the transmitted flux detector (Fig. 10).
Fig. 10 Schematic diagram of the absorption tube on the AC-9. Incident flux ($\Phi_i$) that scatters less than 42° will be reflected off the side of the tube into the transmitted flux detector. The transmitted flux detector collects transmitted flux ($\Phi_t$) and a fraction of the scattered light ($f\Phi_s$). The measured absorption coefficient is calculated using equation 13.
Several scattering corrections exist for the AC-9. Other scattering corrections, not described here, can be investigated through the WetLabs protocol documentation or Zaneveld (1994). The scattering correction method implemented involved subtracting the absorption coefficient at a reference wavelength, $a_{\text{mts}}(\lambda_{\text{ref}})$, where the absorption coefficient is assumed to be zero from the measured absorption coefficient (Equation 12).

$$a_{\text{f}}(\lambda) - a_{\text{w}}(\lambda) = a_{\text{m}}(\lambda) - a_{\text{mts}}(\lambda_{\text{ref}}) \quad (\text{m}^{-1})$$

The reference wavelength generally used is $\lambda_{\text{ref}} = 715$ nm, where the absorption due to particles and dissolved materials is negligible and any measured absorption is due strictly to scattering. In this method, the measured absorption at the reference wavelength, $a_{\text{mts}}(\lambda_{\text{ref}})$, must be temperature and salinity corrected before being applied to the measured absorption coefficients, $a_{\text{m}}(\lambda)$. This corrected absorption measurement is then equal to the total absorption, $a_{\text{T}}(\lambda)$, minus the absorption due to water, $a_{\text{w}}(\lambda)$, which are obtained from pure water calibrations. An important assumption to this method is that the volume scattering function is independent of wavelength. This assumption still allows for the scattering correction to vary with changes in the materials contained with the sample.

After the scattering correction was applied, additional inherent optical properties were calculated from measured and literature values (Table 5). Adding the absorption of pure water, $a_{\text{w}}(\lambda)$ (Pope and Fry 1997) (Table 1), to the absorption due to particles and dissolved materials, $a_{\text{py}}(\lambda)$, gives the total absorption coefficients, $a_{\text{T}}(\lambda)$.

$$a_{\text{T}}(\lambda) = a_{\text{w}}(\lambda) + a_{\text{py}}(\lambda) \quad (\text{m}^{-1})$$
To determine the total beam attenuation coefficients, $c_T(\lambda)$, the scattering due to pure water, $b_w(\lambda)$, was added to the absorption due to pure water to get the beam attenuation component of pure water, $c_w(\lambda)$ (Table 1). The values for the scattering of pure water were obtained from Morel (1974) using equation 9.

$$c_w(\lambda) = a_w(\lambda) + b_w(\lambda) \quad (m^{-1}) \quad (14)$$

The beam attenuation due to water, $c_w(\lambda)$, was then added to the beam attenuation coefficients due to ‘everything else’, $c_{py}(\lambda)$, to calculate the total beam attenuation coefficient, $c_T(\lambda)$.

$$c_T(\lambda) = c_w(\lambda) + c_{py}(\lambda) \quad (m^{-1}) \quad (15)$$

Particle absorption coefficients, $a_p(\lambda)$, were obtained by subtracting the dissolved absorption coefficient, $a_y(\lambda)$, from the absorption due to particles and dissolved material, $a_{py}(\lambda)$.

$$a_p(\lambda) = a_{py}(\lambda) - a_y(\lambda) \quad (m^{-1}) \quad (16)$$

The particle scattering coefficient, $b_p(\lambda)$ was calculated by subtracting the absorption due to particulate and dissolved materials, $a_{py}(\lambda)$, from the beam attenuation due to particulate and dissolved materials, $c_{py}(\lambda)$.

$$b_p(\lambda) = c_{py}(\lambda) - a_{py}(\lambda) \quad (m^{-1}) \quad (17)$$

There is no dissolved component in the scattering coefficient because scattering by dissolved material is assumed to be negligible. Therefore, the subtraction results in the scattering coefficient due to particles only, $b_p(\lambda)$. 
HydroScat-6 – The HydroScat-6 is a fixed angle backscattering sensor that measures the volume scattering function ($\beta(\theta)$) at the nominal angle of 140°. The backscattering coefficient was estimated, with a standard error of ~9%, from the volume scattering function, ($\beta(\theta)$), by using equation 20, where $\chi = 1.08$ (Maffione and Dana 1997).

\[
b_b(\lambda) = 2\pi\chi\beta(140^\circ, \lambda) \quad (m^{-1}) \quad (18)
\]

Wavelengths for the channels on the HydroScat-6 match those on the AC-9 except for the 620 nm channel. The particle backscattering coefficients, $b_{bp}(\lambda)$, are calculated by subtracting half of the pure water scattering coefficient, $b_{bw}(\lambda)$. The values for the scattering of pure water, $b_{bw}(\lambda)$, were obtained from Morel (1974) (Equation 9).

\[
b_{bw}(\lambda) = 0.5\ast b_w(\lambda) \quad (m^{-1}) \quad (19)
\]

\[
b_{bp}(\lambda) = b_b(\lambda) - b_{bw}(\lambda) \quad (m^{-1}) \quad (20)
\]
Table 5. Legend of symbols used for measured and calculated IOP.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Coefficient</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Measured</strong></td>
<td></td>
</tr>
<tr>
<td>$a_{py}$</td>
<td>Particulate and dissolved absorption</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$c_{py}$</td>
<td>Particulate and dissolved beam attenuation</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$a_y$</td>
<td>Dissolved absorption</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$b_b$</td>
<td>Backscattering</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td></td>
<td><strong>Calculated</strong></td>
<td></td>
</tr>
<tr>
<td>$c_T$</td>
<td>Total attenuation</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$a_T$</td>
<td>Total absorption</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$a_p$</td>
<td>Particle absorption</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$b_p$</td>
<td>Particle scattering</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$b_{bp}$</td>
<td>Particle backscattering</td>
<td>m$^{-1}$</td>
</tr>
</tbody>
</table>
Results

Chlorophyll and hydrographic data – Chlorophyll distributions and hydrographic data acquired from discrete water sampling and CTD profiles showed colder, denser, water with higher chlorophyll concentrations at the coast, warmer less dense waters with low chlorophyll concentrations in the oceanic waters and a variable transition zone between the two regions. For reference, stations along the CalCOFI transect 67 were classified into three zones based on temperature and salinity measured during this cruise.

Stations C1 through M2 were designated as coastal stations. At the coast, surface chlorophyll distribution was patchy with maxima found at station M2 (6 mg/m$^3$) and station C1 (4 mg/m$^3$) (Fig. 11). Colder temperatures (10 °C) (Fig.12) and the 25.5 $\sigma_t$ isopycnal (Fig.13) approaching the surface coincided with chlorophyll maxima at these stations.

The region from stations M2 to 67-85 was considered to be in the transition zone. Chlorophyll concentrations, temperature and density were heterogeneous along the transition zone. A local chlorophyll maximum was found below the surface (20 m) between stations 67-80 and 67-85 (>2 mg/m$^3$) (Fig. 11). The 10 °C isotherm (Fig.12) and the 25.5 $\sigma_t$ isopycnal (Fig. 13) reached 20 m between these stations.

The most offshore station 67-90 was considered to be in the oceanic zone. The lowest surface chlorophyll concentration was located at station 67-90 (0.1 mg/m$^3$). The warmest surface temperatures and least dense waters ($\sigma_t = 24.5$) were at the same station. The region between stations 67-90 and 67-85 has a sharp drop in surface chlorophyll concentration as well as an increase in temperature and decrease in $\sigma_t$ value. This
suggests that a boundary of two different water masses existed between these two stations.

Profiles were divided into two sections: 1) above the mixed layer and 2) below the center of the pycnocline (Table 6). The mixed layer depth and pycnocline center depth were determined by taking the first derivative of $\sigma_i$ with respect to depth. The mixed layer depth was defined as the depth at which the first derivative of $\sigma_i$ diverged significantly from zero ($\frac{\Delta \sigma_i}{\Delta z_i} > 0.01$). The center of the pycnocline depth was defined as the depth below the mixed layer where the first derivative of $\sigma_i$ reached a maximum. The mixed layer depth for the oceanic station was the deepest at 50 m.

**Comparison of particle absorption coefficients between an AC-9 and a spectrophotometer** – The average difference between the particle absorption, $a_p$, coefficients from the AC-9 and the spectrophotometer were generally large (Fig. 14). The largest difference was the particle absorption coefficients from the AC-9 at station 67-90 which was on average six times greater than the spectrophotometer readings (Table 7). A slope of 1.0 and an intercept of 0 would indicate there was no difference between the absorption coefficients from the AC-9 and the spectrophotometer. Station M1 at 0 m had the best slope of 1.0 and slope intercept of 0.01. However, station M3 had values which were almost the same with an average difference of 94% between the AC-9 and the spectrophotometer.
Fig. 11  Section of chlorophyll concentrations obtained from discrete water samples from CTD casts and analyzed using fluorometric techniques. CalCOFI stations are shown across the top axis.

Fig. 12  Temperature section of eleven CTD casts along transect 67. The top axis indicates the CalCOFI stations.
Fig. 13 Section of ς_t values from eleven CTD casts along transect 67. CalCOFI stations are labeled across the top axis.

Table 6. Mixed layer and pycnocline depths calculated from ς_t profiles.

<table>
<thead>
<tr>
<th>Station</th>
<th>67-90</th>
<th>67-80</th>
<th>M3</th>
<th>M1</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Layer Depth (m)</td>
<td>50</td>
<td>11</td>
<td>15</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Pycnocline (m)</td>
<td>56</td>
<td>14</td>
<td>25</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>
Note that AC-9 profiles and water sampling occurred at different times (as much as four hours apart). Also water samples came from the surface whereas AC-9 spectra were an average of the top 20 m (except at station M1). At station M1 additional water samples were taken at 10, 20 and 40 m. Therefore, particle absorption coefficients from the AC-9 were averaged from 0-6, 6-15, 16-25, and 36-45 m to match the water sample depths taken at station M1.

**Particle concentration** – Particle scattering, \( b_p \), and particle backscattering, \( b_{bp} \), profiles were used to examine the relative concentration of particles with depth. Even though the coefficients were measured independently from different instruments the profiles usually covaried at any given station (Fig. 15). A line at each station shows the mixed layer calculated from \( \sigma_t \) values (Table 6). Within the mixed layer the relative concentration of particles did not change as shown by the particle scattering and particle backscattering profiles being constant. Coastal particle scattering, \( b_p \), and backscattering, \( b_{bp} \), coefficients within the mixed layer were five times higher than the coefficients in the oceanic mixed layer. Coefficients in the transition zone had intermediate values.

Below the mixed layer, the concentration of particles decreased in the coastal and transition zones. There were a couple of exceptions to this. At station M3 the coefficients peaked just below the mixed layer before decreasing and at stations C1 and M1 the coefficients increased at depth (70 m) though not as high as within the mixed layer. The coefficients at the oceanic station, however, stayed constant just below the mixed layer for another 20 m before decreasing steadily with depth.
Fig. 14 Particle absorption spectra from the spectrophotometer (blue line) and the AC-9 (green crosses). The bottom axis is wavelength in nm and the left axis are particle absorption coefficients in (m⁻¹). Note that scales vary.
Table 7. Regression results from AC-9 and spectrophotometer comparison of particle absorption coefficients. For a perfect comparison, the slope should be 1.0 and intercept 0. Also the peak given is from the spectrophotometer.

<table>
<thead>
<tr>
<th>Peak (nm)</th>
<th>67-90</th>
<th>67-80</th>
<th>M3</th>
<th>M1 – 0m</th>
<th>M1 – 10m</th>
<th>M1 – 20m</th>
<th>M1 – 40m</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average % difference</td>
<td>585</td>
<td>297</td>
<td>94</td>
<td>175</td>
<td>238</td>
<td>131</td>
<td>227</td>
<td>165</td>
</tr>
<tr>
<td>Slope</td>
<td>2.6</td>
<td>1.8</td>
<td>.57</td>
<td>1.0</td>
<td>1.3</td>
<td>.80</td>
<td>1.4</td>
<td>0.76</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>R²</td>
<td>0.94</td>
<td>0.98</td>
<td>0.96</td>
<td>0.95</td>
<td>0.93</td>
<td>0.93</td>
<td>0.89</td>
<td>0.93</td>
</tr>
<tr>
<td>n</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
Fig. 15  The top row shows the particle scattering coefficients \( b_p(\lambda) \) with depth measured by the AC-9. Each color represents a different wavelength (nm). Below are graphs of the particle backscattering coefficient \( b_{bp}(\lambda) \) measured by the HydroScat-6. In both cases, scattering by pure water \( b_w(\lambda) \) has been removed. A line at each station shows the bottom of the mixed layer.
Particle type: living algae or detritus – The distribution of absorbing particles was revealed through the profiles of particle absorption coefficients from the AC-9. These coefficients strongly covaried with in situ fluorescence profiles at all stations (Fig. 16), except at the surface where fluorescence inhibition was noted, indicating that absorption was primarily from fluorescent pigments such as living algal cells or detritus. Distributions varied from coastal, transition and oceanic zones.

Coastal particle absorption coefficients were nearly constant and at a maximum within the mixed layer. Below the mixed layer coefficients decreased and increased again at 70 m though not as high as in the mixed layer, similar to the particle scattering coefficients. These peaks at depth were also seen in the fluorescence profiles. The largest particle absorption coefficients were measured at the coast. Particle absorption coefficients in the transition zone increased slightly at the bottom of the mixed layer, then peaked just below the mixed layer before decreasing to a minimum. Coefficients had intermediate magnitudes and did not increase again at depth. Within the oceanic mixed layer particle absorption coefficients were constant. Coefficients increase below the mixed layer, peak 20-25 m below the mixed layer (70 m), then decrease with depth.

Averaged AC-9 spectra revealed the composition of absorbing particles changing from living algal cells to detrital particles with depth (Fig. 17). Surface water samples analyzed by spectrophotometer provided a higher resolution spectra detrital absorption, $a_d$, and absorption due to phytoplankton, $a_{ph}$, for comparison. AC-9 spectra at the surface resembled the $a_{ph}$ spectra from the spectrophotometer. The resemblance between the AC-9 and $a_d$ spectra increased with depth.
Fig. 16  Vertical profiles of particle absorption coefficients ($a_p \text{ (m}^{-1})$) from the AC-9 (top row) with fluorescence profiles below. The bottom of the mixed layer is indicated by the black line.
Fig. 17 Twenty meter interval averages of spectral particle absorption coefficients from the AC-9 (above) and surface particle absorption coefficients from spectrophotometer (below).
Dissolved material – Data quality of dissolved absorption, $a_y(\lambda)$ profiles at two stations was compromised due to various reasons and as a result were omitted. Data gaps at station C1 (Fig. 18) were due to communication problems with the AC-9. Hence, several archived files were merged together to create one profile. These gaps can also be seen in the particle absorption, $a_p$, and particle scattering, $b_p$, profiles because these coefficients are calculated from the dissolved absorption coefficient, $a_y$, (Table 5). Also, bubbles in the filter compromised data in the top 12 m at station 67-80. An aborted cast, taken immediately before, was used to replace the dissolved absorption coefficients up to 8 m. Data between 8-12 m were interpolated.

At all stations, dissolved absorption coefficients increased with depth, especially the $a_y(412)$ channel (Fig. 18). Mean and standard deviations of the dissolved absorption coefficients were determined for the entire cruise at each wavelength (Fig. 19). The log-linear model fit for the entire cruise yielded an S-value of 0.014 ($R^2 = 0.94$) and this line is superimposed on the data (Fig. 19). Shorter wavelengths showed the greatest variability and the largest absorption coefficients [$a_{y412} = 0.019 - 0.067$ (m$^{-1}$)] (Table 8). Sample size is the number of samples of the cruise after taking 1 m binned medians from the raw data.

The S-value increased with depth at each station, however, there did not appear to be any relationship with the mixed layer. At 20 m intervals the S value was determined (Fig. 20) from dissolved absorption coefficients, $a_y$ using Equation 4 centered on the following depths: 10, 30, 50, 70, 90, 110, 130, 150 m (stations 67-90, M3 and M1) and 10, 30, 50, 70, 90 m (stations 67-80 and C1). Negative values in the 650 and 676 nm
channels were probably a result of inaccurate calibration offsets, and were not used in the regression.

Coastal S values (0.014 nm$^{-1}$) were 50% greater than S-values in the oceanic zone (0.009 nm$^{-1}$). The S values at station M3 did not gradually increase with depth like the other stations but rather peaked sharply at 50 m and then decreased with depth.

Relative concentrations of particulate and dissolved material – The ratio of the particle absorption coefficient ($a_p(\lambda)$) and the ‘net’ absorption coefficient ($a_{py}(\lambda)$) was calculated to estimate the proportion of absorbing material due to particulate matter ($%a_p$) (Equation 21). The same was done with the dissolved absorption coefficients ($%a_y$) (Equation 22). The ‘net’ absorption coefficient ($a_{py}(\lambda)$) used was the total absorption coefficient, $a_T(\lambda)$, minus the absorption due to pure (Equation 13).

\[
%a_p = \frac{a_p(440\,nm)}{a_{py}(440\,nm)} \times 100\%
\]  

\[
%a_y = \frac{a_y(440\,nm)}{a_{py}(440\,nm)} \times 100\%
\]  

At each station, $%a_p$ and $%a_y$ were calculated once within the mixed layer and again for the section below the center of pycnocline (Fig. 21). All profiles were averaged using the 442 nm channel.

Particle absorption was the larger component within the mixed layer, averaging to 66% of the total absorption at all stations (Fig. 21). Coastal stations had a larger particle absorption proportion (70-80%) than the oceanic station (55%).
Dissolved Absorption Coefficients $a_y (\text{m}^{-1})$

![Dissolved Absorption Coefficients](image)

Fig. 18 Vertical profiles of dissolved absorption coefficients ($a_y (\text{m}^{-1})$). A line at each station shows the bottom of the mixed layer.
Fig. 19 The mean dissolved absorption coefficient with standard deviation for each wavelength for the entire cruise (red). Using Bricaud’s model (Equation 4), the slope, $S$, was determined to be 0.014 ($R^2 = 0.94$) and is superimposed (blue).

Table 8. Means ($\overline{X}$), standard deviations ($\sigma$) and number ($N$) of 1 m binned samples of dissolved absorption coefficients, $a_y(\lambda)$ (m$^{-1}$), for each wavelength for the entire cruise.

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>412</th>
<th>442</th>
<th>488</th>
<th>510</th>
<th>532</th>
<th>555</th>
<th>650</th>
<th>676</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{X}$ (m$^{-1}$)</td>
<td>0.056</td>
<td>0.038</td>
<td>0.014</td>
<td>0.010</td>
<td>0.010</td>
<td>0.009</td>
<td>-0.001</td>
<td>-0.001</td>
</tr>
<tr>
<td>$\sigma$ (m$^{-1}$)</td>
<td>0.013$_2$</td>
<td>0.007$_2$</td>
<td>0.002$_1$</td>
<td>0.001$_7$</td>
<td>0.001$_2$</td>
<td>0.001$_2$</td>
<td>0.001$_0$</td>
<td>0.001$_0$</td>
</tr>
<tr>
<td>$N$</td>
<td>702</td>
<td>702</td>
<td>702</td>
<td>702</td>
<td>702</td>
<td>702</td>
<td>702</td>
<td>702</td>
</tr>
</tbody>
</table>
Fig. 20  S-values determined at 20 m intervals from dissolved absorption coefficients using Equation 4. Dissolved absorption spectra averaged every 20 m (left column). Each depth represents a different color. The exponential coefficient, S-value, (right column) increased with depth.
Below the center of the pycnocline dissolved material was as equally important as the particle absorption, averaging to more than half (55%) of the ‘net’ absorption. Contributions were about equal at coastal stations. The proportion of dissolved material in the transition zone was highly variable but still significant.

Particle Size Distribution – Particle concentrations from epifluorescent microscopy and flow cytometry for surface samples were used together to compute a particle size distribution slope (Equation 10) (Fig. 22). Flow cytometry data were added to include smaller diameters when determining the slope. Coastal sites with higher concentrations of larger diatoms at the surface, stations C1 and M2, exhibited lower slopes of 2.41 and 2.48 respectively (Table 10). Station M1, though still a coastal site, had a slightly lower surface chlorophyll concentration (~1 mg/m³) and a slightly higher particle size distribution slope, 2.87. No epifluorescent microscopy data was available for stations 67-90 and 67-80.

Particle size distribution slopes calculated from flow cytometry counts were anomalously high (> 6) probably due to the small size range which the flow cytometer focuses on (0.4-1.0 µm). The slopes were therefore used to indicate the relative change within the given size range. Note that there are no data for station M3 and there is only a surface slope for station C1.

Within the mixed layer, a constant slope indicated no change in the particle size distribution (Fig. 23). Below the mixed layer the increase in the particle size distribution slopes with depth indicated smaller particles became more dominant with depth (Fig. 23).
Fig. 21 Percent contribution of particle, ($%a_p$) and dissolved ($%a_y$) absorption coefficients to ‘net’ absorption coefficients within the mixed layer (top panel) and below the center of the pycnocline (bottom panel) ($\lambda = 442$ nm).
Fig. 22  Concentration of particles for a range of particle diameters (µm) taken from surface waters. Data retrieved through epifluorescent microscope are shown in circles and through flow cytometry are shown in crosses. The best fit line of the log-log regression is superimposed. Slopes are given in Table 9.

<table>
<thead>
<tr>
<th>Diameter (x) (µm)</th>
<th>67-90</th>
<th>67-80</th>
<th>M2</th>
<th>M1</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope</td>
<td>--</td>
<td>--</td>
<td>2.48</td>
<td>2.87</td>
<td>2.41</td>
</tr>
<tr>
<td>R²</td>
<td>--</td>
<td>--</td>
<td>0.83</td>
<td>0.88</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Fig. 23  Particle size distribution slopes taken from only flow cytometry counts (Equation 10). Mixed layer depths are shown only at optical profile stations.
Particle size distribution slopes inferred from *in situ* inherent optical properties are presented here as an alternative method from using discrete water samples. The first method using *in situ* inherent optical properties determines the exponential coefficient, $\gamma$ (gamma) from particle backscattering coefficients, $b_{bp}(\lambda)$, averaged every 20 m, using Equation 11 ($\lambda_o = 676$ nm). Gamma, ($\gamma$), is a value which covaries with the slope of the particle size distribution. The second method takes the ratio of the particle backscattering coefficient ($b_{bp}$), from the HydroScat-6, and the particle scattering coefficient ($b_p$), from the AC-9. The resulting value is a fraction signifying how much scattering occurs in the backward direction. Only ratios averaged every 20 m from the 488 channel are shown.

First, results of gamma, ($\gamma$), values are presented. At all stations gamma values were constant within the mixed layer indicating that the particle size distribution was also constant. Gamma values within the mixed layer were highest offshore ($\gamma = 1.3$), where chlorophyll and particle concentrations were low, and lowest at the coast ($\gamma = 0.5$) where algal blooms were present (Fig. 24). At all stations gamma values increased with depth below the mixed layer indicating that smaller particles began to dominate the system. The oceanic gamma values decreased slightly ($\gamma = 1.1$) at the subsurface chlorophyll maximum (50-90 m) before it increased again below ($\gamma = 1.5$). This indicates that larger particles are more dominant at the subsurface maximum and not at the surface.

All backscattering ratios were low and constant within the mixed layer indicating constant particle size distribution dominated by larger particles, relative to below the mixed layer (Fig. 25). Oceanic backscattering ratios ($b_{bp}/b_p$ (488 nm) $\approx 0.0136$ m$^{-1}$) within the mixed layer were larger than the coastal ratios ($b_{bp}/b_p$ (488 nm) = 0.009 m$^{-1}$),
which indicated that particles in the oceanic zone were more dominated by smaller particles than at the coastal zone.

As was observed with the gamma values, the $b_{bp}/b_p$ ratio increased steadily with depth at all stations below the mixed layer. This indicated an increase in the slope of the particle size distribution or that smaller particles began to dominate the system. The offshore station increased the most and the coastal station increased relatively very little.

To supplement these results from CTD casts, water samples and *in situ* inherent optical property measurements, four SeaWiFS images averaged over varying time spans in May have been added to show the horizontal chlorophyll distribution of the central California coastal waters during and before the cruise. Superimposed on the images are the locations of the CTD (white circles) and optical casts (white crosses) (Fig. 26).

SeaWiFS chlorophyll distributions from the Central Coast region were obtained from the MBARI satellite data archive. The monthly composite image (upper left panel) shows how the chlorophyll concentration was low offshore and increases closer to shore. The greatest variability can be seen in the weekly composites (upper right panel and lower panels) where the southward flowing surface current is characterized by the presence of eddies and fronts. While sampling CalCOFI transect 67, cloud cover was persistent and covered the entire sky, and very little or no satellite data were obtained near the coast. The pixels shown around Monterey Bay for the lower right panel were from a satellite pass one day after the completion of the transect.
Fig. 24  Gamma, the slope of the log-log regression of $b_{bp}(\lambda)$ and wavelength (Equation 11), increases with depth. Mixed layer depths are indicated by the black line.

Fig. 25  The backscattering probability ratio ($b_{bp}/b_p(\lambda = 488 \text{ nm})$) shows the fraction of scattering occurring in the backward hemisphere. Mixed layer depths are marked (black line).
Fig. 26 Horizontal distribution of chlorophyll by SeaWiFS for the Central California coast. Top left panel is a composite mean for the entire month of May 1999. Top right and bottom left are weekly composites for two weeks (May 9-16) and one week (May 17-24) before the cruise. The bottom right panel is for the week of the transect (May 25th – June 1st). CTD stations are in white circles and optical profiling stations are in white crosses.
Discussion

The following discussion will show that the distributions of particles and dissolved materials inferred from analysis of their in situ IOPs (in terms of size, type, and concentration) are similar to distributions obtained using conventional methods such as analyzing discrete water samples. Specifically, we will be dealing with how coastal upwelling and mesoscale eddies both contributed to phytoplankton blooms along CalCOFI transect 67 during May 1999. In order to illustrate the similarity in results between the methods, the dominant constituent, either living algal cells, detritus, or dissolved material, was compared between in situ IOPs and water sampling in four regions along the transect. These four regions are in coastal waters within and below the mixed layer and in oceanic waters within and below the mixed layer. In addition to their role in complementing or confirming results obtained using discrete water sampling, analysis of IOPs also suggests the possibility of real-time viewing of changes in dissolved material composition and particle size distribution with a much finer vertical resolution.

The phytoplankton blooms which occurred along CalCOFI transect 67 (part of the California Current system) were caused by two oceanographic processes: coastal upwelling and mesoscale eddies. Coastal upwelling, which is highest during the late spring and early summer months, brought deeper, colder, nutrient-rich waters into the mixed layer (Barber and Smith 1981, Hutchings et al. 1995) and caused a phytoplankton bloom at coastal stations C1 and M2. This was indicated by lower surface temperatures and higher \( \delta_t \) values at these stations. Mesoscale eddies, which dominate flow patterns in
the transition zone (Strub et al. 1991), can also draw cold waters into the mixed layer (Mooers and Robinson 1984). The phytoplankton bloom offshore (Fig. 11) though not as high as at the coast may have been caused by mesoscale eddies as shown by cooler waters being drawn up between stations 67-85 and 67-80 (Fig. 12). Composite weekly satellite images during May 1999 also indicate that horizontal chlorophyll distributions in the transition zone may have been influenced by mesoscale eddies. Farther offshore, in oceanic waters, there was no mechanism drawing cold nutrient waters into the mixed layer and therefore, phytoplankton concentrations were low at station 67-90. Oceanic waters are typically characterized by warm, dense waters with low phytoplankton concentrations (Kosro et al. 1991, Hood et al. 1990).

The results from the IOPs compared well with water samples retrieved during the cruise and with what is already known in the literature about these four regions. In coastal mixed layers, the dominant constituent was found to be living algal cells. Two optical properties, the particle absorption (a_p) and dissolved absorption (a_y) coefficients, were used to infer this. Because the particle absorption coefficient accounted for a larger proportion of the total absorption coefficient in this region, the dominant constituent was considered to be particulate. Furthermore, the shape of the particle absorption spectrum demonstrated a strong presence of chlorophyll, which indicates that the dominant constituent was living algal cells, not detritus. The results of discrete water sampling also indicate high chlorophyll concentrations within the coastal mixed region, supporting the hypothesis that the dominant constituent was due to living algal cells. Coastal waters along central California in the late spring tend to have increased chlorophyll
concentrations and the phytoplankton are typically dominated by diatoms (Bolin and Abbott 1963, Garrison 1979, Thomas and Strub 1990, Chavez et al. 1991).

Conversely, below the mixed layers in coastal waters dissolved material and detritus were the dominant constituents. Aside from the region just below the mixed layer, where particle absorption coefficients peak, the proportions of dissolved and particle absorption were fairly equally distributed and generally low. In this case, the shape of the particle absorption spectrum showed a weak presence of chlorophyll indicating that the particulate material was more likely due to detritus, not living algal cells. This was supported by a decrease in chlorophyll concentrations below the mixed layer. Unfortunately, no other information from water samples was available to compare with the IOPs. Little information has been published regarding the distribution of dissolved material in this region (Kahru and Mitchell 2001). Bricaud et al. (1981) has stated that in areas not influence by fresh waters the concentration of dissolved material is probably related to biological activity to the extent that this substance is a by-product of the algal cell degradation. This area had $a_y(412 \text{ nm})$ values of 0.06 m$^{-1}$. Other $a_y$ values in coastal waters that are weakly affected by fresh waters, Villefranche Bay, had [0.015-0.40 m$^{-1}$] at $a_y(400 \text{ nm})$, though depth is unknown (Bricaud et al. 1981). Values off Peru ranged from 0.05-0.16 m$^{-1}$ at $a_y(400 \text{ nm})$ (Burt 1958).

Both dissolved material and living algal cells were present in the oceanic mixed layer though both were very low in concentration. Measurements of dissolved absorption in clear waters, such as in the Sargasso Sea, were also very low ($a_y(480 \text{ nm}) = 0.03 \text{ m}^{-1}$) (Ivanoff et al. 1961). Dissolved material, during this cruise, contributed to almost half of
the total absorption in the oceanic mixed layer. The particle absorption spectral shape revealed a weak but present signal of living algal cells.

The region below the oceanic mixed layer can be divided into two sub-regions based on differences in chlorophyll concentration. Sub-region A runs from just below to roughly 20 m below the mixed layer and contains a chlorophyll maximum. In this region, the concentration of living algal cells is maximized. A peak in the particle absorption coefficient as well as the strongest chlorophyll signal out of all the averaged spectra demonstrates this with depth for the oceanic station (Fig. 17). Sub-region B continues from the bottom of sub-region A to the bottom of the cast. In sub-region B dissolved material is the major component of the total absorption and the remaining particle absorption is accounted for by smaller particles (Burt 1958).

An increase in the particle absorption coefficient just below the mixed layer, in sub-region A, may have been due to photoadaptation of pigments. Photoadaptation causes pigment to cell ratios to increase due to low irradiance levels. This typically happens just below the mixed layer in oceanic waters. This is also supported by a subsurface chlorophyll maximum between 50 to 70 m at the oceanic station. This is in contrast to what occurred within the mixed layer above. Particle scattering, $b_p$, and particle absorption, $a_p$, coefficients started low and remained constant within the mixed layer indicating that the pigment to cell ratio within the mixed layer did not change.

The results of the IOPs agreed with much of what is already known using more conventional methods, however, the IOPs differed from more conventional methods in that parameters are obtained in situ, in real-time and at a continuous depth resolution,
which is not possible with discrete water samples. The AC-9 can provide the vertical resolution necessary to monitor change in the composition of dissolved matter by observing change in the S-value. The mean S-value obtained for the entire cruise appears reasonable when compared with previously acquired S-values obtained from other studies using a spectrophotometer (Table 10). Therefore, it appears justified to surmise that this increased resolution does indeed reveal an accurate profile of the change in S-value. In this study, surface S-values were lower than S-values at depth indicating that the absorption efficiency of dissolved material was reduced at the surface which means that the composition of the dissolved material is changing. Photochemical oxidation has been proposed as a mechanism for this reduced absorption efficiency in the surface waters (Zafiriou et al. 1984; Blough and Zepp 1990).

In coastal zones, where river outflow is large, dissolved material can dominate absorption (Bricaud et al. 1981). In these areas, S-values are typically low and dissolved absorption coefficients, $a_\text{d} (\lambda)$, are high while oceanic zones generally exhibit higher values of S and low $a_\text{d} (\lambda)$ coefficients (Blough et al. 1993; Green and Blough 1994, D’Sa et al. 1999). Although dissolved material in the California Current may be affected by river outflow especially in the spring (Apr-May) (Kahru and Mitchell 2001), the author argues that the distribution of dissolved material in May 1999 along the CalCOFI transect 67 seemed more likely to be due to marine processes (Williams and Druffel 1988). For example, waste products and degradation of high algal content in the surface layer may contribute to large S-values in the coastal zone.
Table 10. Ranges for the exponential coefficient, $S$, for absorption due to dissolved material (Eq. 4).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site</th>
<th>$S$ (nm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalle 1966</td>
<td>Baltic, North Sea</td>
<td>0.018</td>
</tr>
<tr>
<td>Kirk 1976</td>
<td>Lakes, coast</td>
<td>0.015</td>
</tr>
<tr>
<td>Lundgren 1976</td>
<td>Baltic</td>
<td>0.014</td>
</tr>
<tr>
<td>Kopelevich and Burenkov 1977</td>
<td>Indo-Pacific</td>
<td>0.017</td>
</tr>
<tr>
<td>Bricaud et al. 1981</td>
<td>Baltic</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>Mauritania</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>Gulf of Guinea</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Mediterranean</td>
<td>0.014</td>
</tr>
<tr>
<td>Okami et al. 1982</td>
<td>East Pacific</td>
<td>0.014</td>
</tr>
<tr>
<td>Kishino et al. 1984</td>
<td>Lake Kizaki</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>Nabeta Bay</td>
<td>0.015</td>
</tr>
<tr>
<td>Carder and Steward 1985</td>
<td>Gulf of Mexico</td>
<td>0.014</td>
</tr>
<tr>
<td>Davies-Colley and Vant 1987</td>
<td>Kiel Harbor</td>
<td>0.016</td>
</tr>
<tr>
<td>Roesler et al. 1989</td>
<td>San Juan Islands</td>
<td>0.017 ± 0.003</td>
</tr>
<tr>
<td>Hoge et al. 1993</td>
<td>Cape Hatteras, Delaware Bight,</td>
<td>0.015-0.023</td>
</tr>
<tr>
<td></td>
<td>Georgia Bight, Gulf of Mexico</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monterey Bay</td>
<td></td>
</tr>
<tr>
<td>Green and Blough. 1994</td>
<td>South Florida</td>
<td>0.015-0.028</td>
</tr>
<tr>
<td></td>
<td>Tamiami River</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>Amazon River and estuary</td>
<td>0.014-0.033</td>
</tr>
<tr>
<td></td>
<td>Sargasso Sea</td>
<td>0.019</td>
</tr>
<tr>
<td>D’Sa et al. 1999</td>
<td>Mid Atlantic Bight</td>
<td>0.016-0.025</td>
</tr>
<tr>
<td></td>
<td>Florida Bay</td>
<td>0.018-0.022</td>
</tr>
<tr>
<td></td>
<td>Gulf of Maine</td>
<td>0.012-0.017</td>
</tr>
<tr>
<td>This study mean, entire transect</td>
<td>Central California</td>
<td>0.014</td>
</tr>
<tr>
<td>This study, in mixed layer</td>
<td>Central California, oceanic zone</td>
<td>0.009</td>
</tr>
<tr>
<td>This study, in mixed layer</td>
<td>Central California, coastal zone</td>
<td>0.013</td>
</tr>
</tbody>
</table>
Higher vertical resolution information of *in situ* data taken real time is not restricted to S-values from the AC-9. It is also obtainable for particle size distribution using the HydroScat-6. Gamma values are obtained with the Hydrosca-6 only and backscattering probability ratios, $b_{bp}/b_p$, are only obtainable by having both the AC-9 and the HS-6 operating simultaneously. Both gamma values and $b_{bp}/b_p$ ratios were similar and also agreed with results from flow cytometry in that, in the mixed layer, the coastal zone is more dominated by larger particles and the oceanic zone is dominated by smaller particles. This result is reasonable since phytoplankton assemblages typically found in oceanic zones are small and coastal zones generally contain large diatoms especially in blooms (Garrison 1979; Stramski and Kiefer 1990; Hood et al. 1991). Also $b_{bp}/b_p$ ratios from Petzold (1972) agreed in so far as the oceanic values ($b_{bp}/b_{p514} = 0.044$) were greater than coastal values ($b_{bp}/b_{p514} = 0.013$).

Conversely, results using the IOP method diverge from those using more conventional methods. The magnitude of the particle absorption coefficients from the AC-9 differed greatly from the spectrophotometer (although spectral shapes often were similar). The differences were greatest at the two offshore stations. While a comprehensive analysis of the differences between the AC-9 and the spectrophotometer was not possible given the currently available data, it appears that the AC-9 may have a tendency to overestimate in regions where particle absorption coefficients are relatively low (such as in oceanic waters).
Conclusions

This research provides a better understanding of how in situ inherent optical properties can be used to determine differences in the material properties of coastal and oceanic regions of the Central California current system. We found that cold, dense coastal waters exhibited higher concentration of larger particles. These observations revealed a large presence of phytoplankton in the mixed layer and detritus below the mixed layer. Dissolved material was also present and made up 30% of the total absorption in the mixed layer and 50% below the mixed layer. Warmer and less dense oceanic waters had equal amounts of living algal cells and dissolved material in the mixed layer though particles sizes were smaller and particle concentrations much lower than the coastal region. Below the subsurface chlorophyll maximum in the oceanic region, dissolved material dominates (60%) though detrital particles are also present. Further sampling of this region during upwelling season, as well as other seasons, would benefit our understanding, especially since only one station was designated as being in an oceanic region.

The change in the S-value with depth is an interesting area for continued investigation. The optical profiler used in this research provides the high vertical resolution needed for analyzing changes in the composition of dissolved material. However, spectrophotometric analysis of dissolved material (which was absent in this study) should accompany this type of investigation. Due to the high proportions of dissolved materials found in oceanic waters in this study, further investigation into the ratio of dissolved absorption to total absorption would be valuable.
It is important to note that information from *in situ* inherent optical properties is not intended to replace data acquired using discrete water sampling methods. Rather, it can provide a more efficient method for gathering information about dissolved and particulate material and provides high vertical resolution which is otherwise unattainable through discrete water sampling.
References


