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Spatial and Temporal Variability of Remotely Sensed Ocean Color Parameters in Coral Reef Regions

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Spatial and Temporal Variability of Remotely Sensed Ocean Color
Parameters in Coral Reef Regions

by

Daniel Brooks Otis

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy
College of Marine Science
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ABSTRACT

The variability of water-column absorption due to colored dissolved organic matter (CDOM) and phytoplankton in coral reef regions is the focus of this study. Hydrographic and CDOM absorption measurements made on the Bahamas Banks and in Exuma Sound during the spring of 1999 and 2000 showed that values of salinity and CDOM absorption at 440nm were higher on the banks (37.18 psu, 0.06 m$^{-1}$), compared to Exuma Sound (37.04 psu, 0.03 m$^{-1}$). Spatial patterns of CDOM absorption in Exuma Sound revealed that plumes of CDOM-rich water flow into Exuma Sound from the surrounding banks. To examine absorption variability in reef regions throughout the world, a thirteen-year time series of satellite-derived estimates of water-column absorption due to CDOM and phytoplankton were created from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data. Time series data extracted adjacent to coral reef regions showed that variability in absorption depends on oceanographic conditions such as circulation patterns and winds as well as proximity to sources of light-absorbing materials that enter the water column, such as from terrestrial runoff. Waters near reef regions are generally clear, exhibiting a lower "baseline" level of CDOM absorption of approximately 0.01 m$^{-1}$ at 443nm. The main differences between regions lie in the periods during the year when increased levels of absorption are observed, which can be triggered by inputs of terrestrially-derived material, as in the Great Barrier Reef lagoon, or wind-driven
upwelling as in the Andaman Sea and eastern Pacific Ocean near Panama. The lowest CDOM absorption levels found were approximately 0.003 m\(^{-1}\) at 443nm near the islands of Palau and Yap, which are removed from sources of colored materials. The highest absorption levels near reefs were associated with wind-driven upwelling during the northeast monsoon on the Andaman coast of Thailand where values of CDOM absorption at 443nm reached 0.7 m\(^{-1}\). Simulations of the underwater light field based on satellite-derived absorption values revealed that changes in absorption have a strong influence on light levels to which corals are exposed, particularly in the ultraviolet region of the spectrum, where CDOM is the primary absorber of light. Episodes of coral bleaching during 1998 and 2002 were found to be associated with elevated seawater temperatures as well as decreased levels of CDOM absorption, indicating that corals were exposed to light stress along with thermal stress during periods of bleaching.
1. INTRODUCTION

1.1 RATIONALE FOR THIS STUDY

Waters surrounding coral reefs are generally clear, allowing symbiotic algae called zooxanthellae to harvest light to provide energy for photosynthesis, allowing reefs to form the basis of highly productive ecosystems in otherwise nutrient-poor waters. However, reefal waters are not uniformly clear, in space nor in time. The spatial and temporal variability of light-absorbing compounds found in waters surrounding coral reefs is the focus of this study.

This study will examine two main factors, chlorophyll and colored dissolved organic matter (CDOM), which influence light levels that coral reefs are exposed to in terms of ultraviolet radiation (UVR), which ranges from 280nm to 400nm, and photosynthetically active radiation (PAR), which effectively ranges from 400nm to 700nm. Elevated levels of both UVR and PAR have been shown to cause oxidative stress in reef-building corals and have been implicated, along with elevated seawater temperatures, in episodes of mass coral bleaching events, a stress response by corals resulting in a whitening of coral tissues due to the loss of symbiotic algae living within coral tissues (Lesser 2011). By examining the concentrations of light-absorbing constituents in the water column adjacent to coral reefs, an estimate of the underwater light field incident upon coral reefs can be determined.
During the 1997-1998 worldwide bleaching event, striking differences were observed between corals found in the inner lagoon of an island in the Seychelles and corals living on the seaward slopes of the same island (Iluz et al. 2008). Corals in the lagoon exhibited much lower levels of bleaching and post-bleaching mortality than corals living on the seaward slopes of the island, even though daytime water temperatures in the lagoon (~35°C) are much warmer than in the surrounding waters (~28°C). However, water in the lagoon is much less clear than surrounding ocean water, particularly with regard to the absorption of ultraviolet radiation (UVR). Accumulations of decomposing seagrass blades along the shore of the lagoon were observed to leach colored substances visible to the naked eye (Iluz et al. 2008). Light absorption by the leachate was measured and found to be highly absorbing in the UV region of the visible spectrum, leading the researchers to conclude that the colored substances in the lagoon provided a UV screen which protected the corals from extensive bleaching, even though they were exposed to much higher temperatures than nearby corals outside the lagoon (Iluz et al. 2008).

The Islands of Palau and Yap also provide a contrast in observed bleaching on reefs experiencing similar thermal conditions. Palau and Yap are located approximately 450km apart in the Philippine Sea, but experienced much different levels of coral bleaching during the 1997-1998 event. Severe bleaching and widespread post-bleaching mortality was observed on several Palauan reefs, while only a single observation of moderate bleaching was reported on Yap. One notable difference between the two islands is the presence of well developed mangrove communities on Yap compared with many fewer mangroves and overall clearer water on Palau (Spaulding et al. 2001, Hallock
Muller, pers. comm.). Mangrove communities are rich in CDOM, which is a strong absorber of UVR (Jennerjahn and Ittekkot 2002).

Light levels experienced by coral reefs are extremely variable on time scales ranging from hours to months, depending on tidal flow, incident solar radiation, and proximity to sources of light-absorbing compounds such as rivers, mangrove forests, population centers, and sites of coastal development. While many previous studies have examined environmental conditions in coral reef regions, particularly during bleaching episodes, few have examined the levels of light-absorbing compounds in the water column, which can have a strong influence on the underwater light field. Ayoub (2009) found that absorption due to CDOM in the Florida Keys is higher on reefs adjacent to intact shorelines containing mangroves compared to developed shorelines. Other studies have found that CDOM is the primary absorber of UVR in waters surrounding coral reefs (Ayoub 2009, Zepp et al. 2008, Otis et al. 2004, Anderson et al. 2001) and therefore is highly influential on the underwater light field to which corals are exposed.

This study will examine the variability of the absorption due to CDOM and phytoplankton on a variety of spatial and time scales. Chapter 3 contains previously published data (Otis et al. 2004), collected in the Islands of the Bahamas, which examined changes in CDOM absorption and chlorophyll concentrations on time scales of hours to days in an area of less than 100 km². In Chapter 4, the variability of CDOM and chlorophyll are examined over a 12-year time period in several reef regions throughout the world using remotely-sensed data collected by satellites along with simulations of the underwater light field to which corals are exposed in those regions. Chapter 5 examines the connection between coral reef bleaching and variability of CDOM and chlorophyll in
reef regions where bleaching has been observed. Introductory material on coral reefs and bleaching can be found in the appropriate chapters, while Chapter 2 provides an introduction to optical oceanography, particularly those aspects pertaining to remote sensing of ocean color.

1.2 DEFINITION OF TERMS AND SYMBOLS

Tables 1.1 and 1.2 define the important symbols and subscripts that will be used in this study.

**Table 1.1** Common oceanographic symbols used in this study.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ</td>
<td>Wavelength of light</td>
<td>nm (1 × 10⁹m)</td>
</tr>
<tr>
<td>a</td>
<td>Absorption</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>b</td>
<td>Scattering</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>R_{rs}</td>
<td>Remote sensing reflectance (at sensor)</td>
<td>sr⁻¹</td>
</tr>
<tr>
<td>r_{rs}</td>
<td>Remote sensing reflectance (subsurface)</td>
<td>sr⁻¹</td>
</tr>
<tr>
<td>K</td>
<td>Diffuse attenuation coefficient</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>[Chl]</td>
<td>Chlorophyll concentration</td>
<td>mg/m³</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically Available Radiation</td>
<td>*Einstein/m²•day</td>
</tr>
<tr>
<td>SST</td>
<td>Sea surface temperature</td>
<td>°C</td>
</tr>
</tbody>
</table>

*An Einstein represents 6.022 × 10²³ (1 mol) of photons

**Table 1.2** Common subscripts for symbols used in this study

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Meaning</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDOM</td>
<td>Chromoporic dissolved organic matter</td>
<td>a_{CDOM}</td>
</tr>
<tr>
<td>p</td>
<td>Particulate</td>
<td>b_{bp}</td>
</tr>
<tr>
<td>ph</td>
<td>Pigmented</td>
<td>a_{ph}</td>
</tr>
<tr>
<td>w</td>
<td>Water</td>
<td>a_{w}, b_{bw}</td>
</tr>
<tr>
<td>d</td>
<td>Downwelling</td>
<td>K_{d}</td>
</tr>
<tr>
<td>b</td>
<td>Backwards direction</td>
<td>b_{b}</td>
</tr>
<tr>
<td>Card</td>
<td>Carder chlorophyll concentration</td>
<td>[Chl]_{Card}</td>
</tr>
<tr>
<td>min</td>
<td>minimum</td>
<td>*MAC_{min}</td>
</tr>
<tr>
<td>max</td>
<td>maximum</td>
<td>*MAC_{max}</td>
</tr>
<tr>
<td>range</td>
<td>range</td>
<td>*MAC_{mg}</td>
</tr>
<tr>
<td>sig</td>
<td>significance</td>
<td>*MAC_{sig}</td>
</tr>
</tbody>
</table>

*MAC represents the mean annual cycle, or seasonal cycle, of any quantity, sometimes referred to as a climatology
2. BACKGROUND

2.1 INTRODUCTION

For readers unfamiliar with optical oceanography, a brief introduction to concepts relating to this study is presented here. More complete discussions of this subject matter can be found in Kirk (1994), Mobley (1994), or Spinrad, Carder, and Perry (1994). This discussion will focus on the aspects of optical oceanography relevant to satellite remote sensing.

2.2 THE NATURE OF LIGHT

The term light refers to one type of electromagnetic energy. The wavelength of light is the length of a complete cycle of the light wave. Equation 2.1 relates the wavelength of light, \( \lambda \), to its frequency, \( \nu \), which has units of inverse time (s\(^{-1}\)). In equation 2.1, \( c \) represents the speed of light in a vacuum, which is constant.

\[
\lambda = \frac{c}{\nu} \quad (2.1)
\]
The relationship between the energy of a light wave, \( E \), and its wavelength, \( \lambda \), is given by equation 2.2. In this equation, \( h \) is Planck's constant and is equal to \( 6.63 \times 10^{-34} \text{ J} \cdot \text{s} \) (Kirk 1994).

\[
E = \frac{hc}{\lambda} \tag{2.2}
\]

Equation 2.2 shows that an inverse relationship exists between the energy of light and its wavelength. Electromagnetic radiation of various types exists in a spectrum based on energy (Fig. 2.1).

![Electromagnetic spectrum](image)

**Figure 2.1** Electromagnetic spectrum. Image created by Philip Ronan.

Gamma rays and X-rays exist on the high energy, high frequency end of the spectrum, while less energetic types of electromagnetic radiation with longer wavelengths such as microwaves and radio waves are found on the low energy, low frequency end of the spectrum (Fig. 2.1). This study will focus on the ultraviolet (UV) and visible portions of
the spectrum. The UV portion of the spectrum can be partitioned into two main regions, the UV-B portion, from 280nm to 320nm and the UV-A portion from 320nm to 400nm, while the visible spectrum consists of light with wavelengths from 400nm to 700nm.

2.3 LIGHT-ATMOSPHERE INTERACTIONS

Most of the solar radiation reaching the Earth is in the visible region of the electromagnetic spectrum (390nm-700nm) (Wehrli 1985) (Figure 2.2). Due to absorption by gases in the atmosphere, some of this light never reaches the sea surface (Fig. 2.2). Gases in the atmosphere, such as water vapor (H\textsubscript{2}O), oxygen gas (O\textsubscript{2}), and carbon dioxide (CO\textsubscript{2}) absorb light in certain regions of the spectrum, which renders the atmosphere opaque to light of those wavelengths. In other regions of the spectrum, "atmospheric windows" exist where the atmosphere is relatively transparent to solar radiation. In the visible and near-UV regions (300nm-700nm), the atmosphere is not highly absorbing and therefore most light from the sun reaches the sea surface.
Figure 2.2 Solar radiation spectrum. Radiation at the top of the atmosphere is given by the yellow region. Radiation reaching the sea surface is given by the red region. Image created by Robert A. Rohde / Global Warming Art.

Upon reaching the sea surface, light enters the water and is the primary energy source for phytoplankton and other photosynthetic organisms in the ocean. When light enters a volume of seawater, some of the incident light is absorbed within the volume of water, some of the light is scattered, and some is transmitted. Energy contained in the light which is absorbed is taken up by particles or molecules within the volume of water and can be dissipated as heat, used for photosynthesis, or re-emitted with a loss of energy at another (longer) wavelength in a process known as fluorescence. Scattered light is reflected out of the incident beam in another direction (can be in the forward or backward direction in any angle) by particles or molecules within the water. Transmitted light is the portion of the incident beam that exits the volume of water unaffected. This can be represented by equation 2.3 from Mobley (1994).
\[
\Phi_i(\lambda) = \Phi_a(\lambda) + \Phi_s(\lambda) + \Phi_t(\lambda)
\]  \hspace{1cm} (2.3)

The incident light flux (energy/sec) is represented by \(\Phi_i(\lambda)\) and the portions of the incident light which are absorbed, scattered, and transmitted are represented by \(\Phi_a(\lambda), \Phi_s(\lambda),\) and \(\Phi_t(\lambda)\) respectively. The letter lambda indicates that each of these quantities varies as a function of the wavelength of light, measured in nanometers, which is \(1 \times 10^{-9}\) m.

2.4 ABSORPTION IN NATURAL WATERS

2.4.1 Absorption due to pure water

Absorption can be due to pure water itself, particles, or dissolved materials (Kirk 1994). Pure water absorbs strongly toward the red end of the visible spectrum, as shown in figure 2.3.

![Figure 2.3 Absorption by pure water (Smith and Baker (1981), Pope and Fry (1997), Sogandares and Fry (1997)).](image)
2.4.2 Absorption due to particles

For the purposes of optical oceanography, particles in natural waters are placed into one of two groups, algal particles or non-algal particles. Algal particles represent phytoplankton which contain light-absorbing pigments and have absorption spectra characterized by a peak around 440nm and another peak around 675nm. In terms of absorption, non-algal biogenic particles are commonly considered as detritus and also have a characteristic absorption spectrum, which decays exponentially with increasing wavelength. Dust and suspended sediments will not be considered here. Sample absorption spectra of algal and non-algal particles using data from Bahamas (this study) are shown in Figure 2.4.

![Spectral absorption of algal and non-algal particles.](image)

**Figure 2.4** Spectral absorption of algal and non-algal particles.
2.4.3 Absorption due to Chromophoric Dissolved Organic Matter (CDOM)

Chromophoric dissolved organic matter and its absorption properties are central to this study and will be described in the following sections.

2.4.3.1 Humic substances

Humic substances are a class of biogenous compounds found in soil, which are polymers made up of aromatic ring structures linked by long-chain alkyl chains (Kirk 1994), and are derived from the decomposition of plant matter by microbes (Harvey and Boran 1985). Water-soluble humic substances are extracted as rainwater percolates through soil and drains into rivers, streams, and lakes, which can impart a yellow color to the water. This light absorbing dissolved material is known as Gelbstoff, gilvin, or yellow substance. Another term is chromophoric dissolved organic matter (CDOM), which is defined as the chemically complex, light-absorbing portion of the dissolved organic matter (DOM) pool found in natural waters (Blough and Del Vecchio 2002).

2.4.3.2 Importance of CDOM

This portion of the DOM pool is important for three main reasons. First, because CDOM absorbs light strongly in the ultraviolet and blue portions of the spectrum (Fig. 2.5), it has a profound effect on the underwater light field, particularly at UV wavelengths, which have been shown to be particularly damaging and have been implicated in coral bleaching (Gleason and Wellington 1993, Dunne and Brown 1996, Anderson et al. 2001). In clear waters surrounding coral reefs, absorption by CDOM often dominates total absorption in the water column and is the main factor influencing the underwater light field (Siegel et al. 2002, Zepp et al. 2008). Second, light absorption by CDOM leads to a series of photochemical reactions which degrade CDOM and its
light-absorbing capabilities. This can lead to a feedback where photodegradation of CDOM leads to increased penetration of solar radiation and therefore further degradation of CDOM. Third, as the use of ocean color remote sensing has expanded, the need to include absorption by CDOM has become apparent, particularly in coastal areas where CDOM absorption compromises estimates of phytoplankton biomass (Carder et al. 1989, Blough and DelVecchio 2002). As ocean color satellite sensors and remote sensing algorithms have become more refined, absorption due to CDOM has been included, increasing the accuracy of phytoplankton biomass estimates (Carder et al. 1999).

2.4.3.3 Sources of CDOM

In coastal waters, CDOM is primarily comprised of terrestrially-derived humic and fulvic acids delivered by rivers and streams. An inverse relationship between CDOM and salinity is observed in these waters and indicates a freshwater source of CDOM (Blough and DelVecchio 2002). The sources and composition of CDOM in open ocean environments are not as well understood (Nelson and Siegel 2002, DelCastillo 2005). Harvey and Boran (1985) found that humic and fulvic acids in the open ocean may result from the reaction of fatty acids released by phytoplankton and are distinct from terrestrial humic substances. A study by Bricaud et al. (1981) suggested that phytoplankton do not directly produce CDOM. However, phytoplankton may instead act as a source of material that is then converted into CDOM by heterotrophic bacteria (Tranvik 1993). In a study based on satellite measurements, Kahru and Mitchell (2001) found that while CDOM absorption values in the California Current were well correlated with chlorophyll concentrations in offshore and outershelf waters, they were not well correlated in inshore waters, suggesting that phytoplankton may be a principle source of
CDOM in offshore waters but not in the coastal zone. Specific pathways of CDOM formation in the open ocean are complex and not well defined, but two main sources in surface waters are in situ production due to excretion by zooplankton, algae, and bacteria, along with transport of CDOM-rich deeper waters to the surface by convective overturn (Nelson and Siegel 2002).

Marine organic matter can be chemically differentiated based its source. The carbon skeleton of terrestrial organic matter derived from soils is larger and more chemically complex with more aromatic rings than marine organic matter, which has smaller, simpler, and more aliphatic carbon skeletons (Del Castillo 2005). These chemical differences between marine and terrestrial organic matter lead to differences in optical properties.

Coastal areas isolated from river inputs represent a case similar to offshore environments, where CDOM concentrations are often low and do not show a clear relationship with salinity (Obernosterer and Herndl 2000). In the extremely clear waters of the Bahamas, for example, where CDOM concentrations are very low, sediment porewaters have been found to be a source of CDOM (Boss and Zaneveld 2003). Values of CDOM absorption in this region are positively correlated with salinity and will be discussed in Chapter 3.

2.4.3.4 CDOM sinks

Several mechanisms exist for the breakdown of CDOM in estuarian and marine environments including flocculation, precipitation, and photochemical degradation. Of these, the photochemical pathway appears to be most significant, particularly in marine environments. Exposure of CDOM to ultraviolet radiation results in substantial
photochemical loss of absorption and fluorescence properties on relatively short time scales (Blough and Del Vecchio 2002). Under irradiance conditions found in nature, absorption due to CDOM can be reduced by 50% or more over time scales of weeks to months (Vodacek et al. 1997, Nelson et al. 1998). Several studies have examined the role that bacteria play in breaking down CDOM, and have found that, although the loss of CDOM absorption due to direct microbial degradation of CDOM is very low (Moran et al. 2000), photochemical degradation of CDOM leads to products that are subsequently metabolised by bacteria (Kieber et al. 1989, 1990; Wetzel et al. 1995).

2.4.3.5 Optical properties of CDOM

The absorption spectra of CDOM are often fit to the following expression in equation 2.4:

\[ a_{CDOM}(\lambda) = a_{CDOM}(\lambda_0) \cdot e^{-S(\lambda - \lambda_0)} \]  

(2.4)

In this equation, \( a(\lambda) \) is the absorption at a particular wavelength, \( a(\lambda_0) \) is the absorption at a given reference wavelength, and \( S \) is the slope parameter, which describes how quickly the absorption decreases with increasing wavelength. Blough and Del Vecchio (2002) compiled values from an array of studies conducted worldwide and found that CDOM absorption values at 355nm ranged from 0.05m\(^{-1}\) near Bermuda to nearly 200m\(^{-1}\) in the Suwannee River in North Florida, while values of \( S \) ranged from 0.011 to 0.025. Values of CDOM absorption and \( S \) found in the Bahamas in this study will be discussed in Chapter 3.

To illustrate the spectral nature of CDOM absorption in different water bodies, absorption spectra from Tampa Bay, the West Florida Shelf, and the Bahamas are shown in Figure 2.1. Spectra were generated based on Equation 2.1 using experimental values of
$a_{\text{CDOM}}$ and $S$ from this study (Bahamas), Chen et al. (2007) (Tampa Bay), and Green and Blough (1994) (West Florida Shelf). The absorption spectrum of detrital, or non-algal particles (Figure 2.4), is not distinguishable from absorption due to CDOM (Figure 2.5) using remotely-sensed ocean color data. However, in clear waters, particulate detritus contributes very little to the overall absorption (Nelson et al. 1998), so these two absorption terms are combined and will be referred to as $a_{\text{CDOM}}$ throughout this study.

Figure 2.5 Spectral absorption by CDOM in three locations.
2.5 SCATTERING IN NATURAL WATERS

Scattering in natural waters is defined in terms of the scattering coefficient, $b$, which has units of m$^{-1}$. The scattering coefficient can be thought of as the magnitude of scattering and can be due to pure water ($b_w$) or particles ($b_p$). In addition to magnitude, there is also an angular component to scattering, called the phase function, with units of sr$^{-1}$, which describe a solid angle. The product of the scattering coefficient and the phase function is called the volume scattering function and completely describes scattering due to particles or molecules (Mobley 1994). Complete determinations of the phase function and volume scattering functions are rarely computed. Instead, the scattering coefficient is partitioned into forward scattering ($b_f$) and backscattering ($b_b$) portions. Of particular importance for remote sensing applications is the fraction of light scattered in the backwards direction ($b_b$) and can be further partitioned into contributions from pure water ($b_{bw}$) and particles ($b_{bp}$). Use of the backscattering coefficient in remote sensing is described in the next section.

2.6 REMOTE SENSING OF OCEAN COLOR

As shown in previous sections, natural waters contain a mixture of dissolved and particulate constituents which, by absorbing and scattering light, make varying contributions to the underwater light field and lead to highly variable optical properties. Two main categories of optical properties exist: Inherent optical properties (IOPs) and apparent optical properties (AOPs). IOPs are properties that depend only on the optical properties of the medium, such as absorption and scattering coefficients. AOPs, such as
the diffuse attenuation coefficient or the irradiance reflectance, are properties that depend on the optical properties of the medium, but also on the angular structure of the ambient light field (Mobley 1994). When using satellite ocean color imagery to investigate biological, chemical, or physical processes in the ocean, one main goal is to estimate IOPs in the water column based on AOPs observed by the satellite sensor.

When light enters a body of water, it is absorbed and scattered by compounds in the water and a portion of the light that originally entered the water is scattered in the backwards direction back out of the water through the air-water interface. After removal of the effects of the atmosphere on the upwelling light field, algorithms used to interpret ocean color measurements made from space usually involve taking spectral ratios of remote-sensing reflectance, $R_{rs}$, which is a measure of how much downwelling light is reflected back out of the water and is visible to a sensor above the surface.

Numerous algorithms have been used to estimate the concentration of chlorophyll ([Chl]). The algorithm used in the Coastal Zone Color Scanner (CZCS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is based on the $R_{rs}$ (443nm)/ $R_{rs}$ (550nm) and $R_{rs}$ (490nm)/ $R_{rs}$ (550nm) ratios. While useful for estimating chlorophyll in waters where optical properties are determined primarily by phytoplankton, these algorithms don’t take into account absorption by dissolved materials and can lead to errors in derived pigment concentrations of up to 133% (Carder et al. 1991). In order to estimate the absorption due to CDOM in surface waters, an algorithm is needed that can further spectrally decompose the radiance signal reaching the sensor. One approach is to utilize a radiance band closer to the UV region of the spectrum. Such an algorithm has been developed for the Moderate Resolution Imaging Spectroradiometer (MODIS), which uses both the
412nm and the 443nm band in order to derive the absorption due to CDOM (Carder et al. 1999). This algorithm takes advantage of the fact that CDOM absorbs more strongly at 412nm than at 443nm, while phytoplankton absorbs more strongly at 443nm than at 412nm. Because the SeaWiFS sensor also has a 412nm band, this algorithm can be applied to estimate CDOM absorption as well as chlorophyll concentration from SeaWiFS imagery. Another algorithm to estimate inherent optical properties of the water column based on reflectance measurements is the quasi-analytical (QAA) algorithm (Lee et al. 2002, 2009). Both the Carder (1999) and Lee (2009) algorithms take absorption by CDOM into account. Because implementation is more streamlined computationally, the QAA algorithm was used in this study to estimate the absorption due to CDOM and detritus at 443nm ($a_{\text{CDOM}}(443)$) as well as the absorption coefficient due to phytoplankton at 443nm ($a_{\text{ph}}(443)$). Using the QAA derived $a_{\text{ph}}(443)$, chlorophyll concentrations were determined using the methods of Carder et al. (1999), which is discussed below. The following equations can be found in Lee et al. (2009) and Carder et al. (1999) along with complete discussions of each algorithm.

Underlying both the Carder and Lee algorithms is the idea that remote sensing reflectance ($r_{rs}$) can be defined as a function of the backscattering coefficient and the absorption coefficient, which is described in Gordon et al. (1988) and is given by equation 2.5.

$$r_{rs}(\lambda) = g_0 u(\lambda) + g_1 [u(\lambda)]^2 \quad (2.5)$$
In equation 2.5, \( u \) is ratio of the backscattering coefficient to the sum of the absorption and backscattering coefficients as expressed in equation 2.6.

\[
\begin{align*}
  u &= \frac{b_b}{a + b_b} \\
  \text{(2.6)}
\end{align*}
\]

Equation 2.5 can be solved for \( u \), which gives equation 2.7. The coefficients \( g_0 \) and \( g_1 \) cannot be determined using remotely sensed data, as they depend on the particle phase function. For this study, averaged values from Gordon et al. (1988) and Lee et al. (1999) are used where \( g_0 = 0.0895 \) and \( g_1 = 0.1247 \) (Lee et al. 2009).

\[
\begin{align*}
  u(\lambda) &= \frac{-g_0 + [(g_0)^2 + 4g_1r_{rs}(\lambda)]^{1/2}}{2g_1} \\
  \text{(2.7)}
\end{align*}
\]

Implementation of the QAA requires the calculation of \( r_{ns} \) just below the sea surface as viewed from nadir using equation 2.8, where \( R_{rs} \) is the remote sensing reflectance measured at the satellite.

\[
\begin{align*}
  r_{rs} &= R_{rs}(\lambda)/(0.52 + 1.7R_{rs}(\lambda)) \\
  \text{(2.8)}
\end{align*}
\]

Once \( r_{ns} \) below the surface is determined, the total absorption, \( a(\lambda) \), at a reference wavelength is calculated. For this study 555nm was used as the reference wavelength and \( a(555) \) was calculated using equations 2.9 and 2.10.
\[ \chi = \log \left( \frac{r_{rs}(443) + r_{rs}(490)}{r_{rs}(555) + s \frac{r_{rs}(667)}{r_{rs}(490)} r_{rs}(667)} \right) \]  \hspace{1cm} (2.9)

\[ a(555) = a_w(555) + 10^{-1.146 - 1.366 \chi - 0.469 \chi^2} \]  \hspace{1cm} (2.10)

To calculate \(a(\lambda)\), an expression for \(b_b\) is required, which is given by equations 2.11 and 2.12.

\[ b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda_0) \left( \frac{\lambda_0}{\lambda} \right)^{\eta} \]  \hspace{1cm} (2.11)

\[ \eta = 2.0 \left( 1 - 1.2 \times \exp \left( -0.9 \frac{r_{rs}(443)}{r_{rs}(555)} \right) \right) \]  \hspace{1cm} (2.12)

The total absorption coefficient at 443nm can now be calculated using equation 2.13.

\[ a(443) = \frac{[1-u(443)] [b_{bw}(443) + b_{bp}(443)]}{u(443)} \]  \hspace{1cm} (2.13)

The backscattering coefficient at 443nm due to pure water (\(b_{bw}\)) is known (Morel 1974). The total absorption coefficient is now decomposed into the contribution by CDOM and detritus along with the contribution by phytoplankton using equations 2.14 - 2.18. First, the spectral slope (S) of CDOM absorption is estimated from \(r_{rs}(443)\) and \(r_{rs}(555)\) (Lee et al. 2009).
\[
S = 0.015 + \frac{0.002}{0.6 + \frac{r_s(443)}{r_s(555)}} \tag{2.14}
\]

From \(S\), \(\xi\) can be calculated using equation 2.15.

\[
\xi = e^{S(443-412)} \tag{2.15}
\]

Then calculate \(\zeta\), using equation 2.16.

\[
\zeta = 0.74 + \frac{0.2}{0.8 + \frac{r_s(443)}{r_s(555)}} \tag{2.16}
\]

Finally, \(a_{CDOM}\) and \(a_{ph}\) at 443nm are calculated using equations 2.17 and 2.18.

\[
a_{CDOM}(443) = \frac{[a(412) - \zeta a(443)]}{\xi - \zeta} - \frac{[a_w(412) - \zeta a_w(443)]}{\xi - \zeta} \tag{2.17}
\]

\[
a_{ph}(443) = a(443) - a_{CDOM}(443) - a_w(443) \tag{2.18}
\]

The absorption coefficients due to dissolved materials and detritus (\(a_{CDOM}\)) and phytoplankton (\(a_{ph}\)) at 443nm have now been calculated. The absorption coefficient due to pure water (\(a_w\)) at 443nm is known (Pope and Fry 1997).
To derive an estimate of the chlorophyll concentration, the relationship between $\text{aph}(443)$ and $\text{aph}(675)$ developed in Carder et al. (1999) will be used and is given in equation 2.19.

$$
\text{aph}(\lambda) = a_0(\lambda)\exp \left[ a_1(\lambda) \tanh \left( a_2(\lambda) \ln \left( \text{aph}(675)/a_3 \right) \right) \right] \times \text{aph}(675) \quad (2.19)
$$

In equation 2.19, $\lambda$ is 443nm, which was calculated previously using the equations from Lee et al. (2009). The coefficients $a_0$, $a_1$, $a_2$, and $a_3$ are from Carder et al. (1999) and are for areas without packaged pigments, which is appropriate for clear waters adjacent to coral reefs. A complete discussion of packaged pigments and how they relate to this algorithm can be found in Carder et al. (1999). Chlorophyll concentration, which has units of mg/m$^3$ is proportional to aph(675) and is calculated using equation 2.20 from Carder et al. (1999).

$$
[\text{Chl}]_{\text{Car,d}} = P_0 \times [\text{aph}(675)]^{P_1} \quad (2.20)
$$

Coefficients $P_0$ and $P_1$ are from Carder (1999) for regions without packaged pigments. Values for coefficients used in equations 2.5, 2.7, 2.19, and 2.20 can be found in Table 4.4.

Using remotely-sensed ocean color satellite data, the two primary light absorbing compounds in waters near coral reefs, CDOM and chlorophyll, can now be estimated using equations 2.5-2.20.
3. CDOM IN THE BAHAMAS BANKS

Note to Reader

Portions of this chapter have been previously published in the journal *Coral Reefs*, published by Springer, in 2004 (ISBN 0722-4028) and are utilized with the permission of the publisher. Co-authors of this previously published work are Kendall L. Carder, who provided guidance editing the manuscript, and James E. Ivey and David C. English, who assisted with data collection.

3.1 INTRODUCTION

Chromophoric or colored dissolved organic matter (CDOM), also known as gelbstoff, yellow matter, or gilvin, absorbs primarily ultraviolet and blue light and plays an important role in determining the underwater light field. In the open ocean, where coastal runoff and riverine input are negligible on annual time scales and chlorophyll $a$ concentrations ([Chl]) are typically less than 0.5 mg/m$^3$, CDOM absorption dominates the total attenuation budget and is the major factor controlling the penetration of ultraviolet radiation (UVR) (Nelson and Siegel 2002). In many coastal areas, the primary source of CDOM is freshwater input from terrestrial runoff. However, in subtropical bank regions such as the Bahamas that lack fluvial inputs, substrate-related sources, particularly seagrass beds and coral reefs, have been found to be the primary CDOM
sources (Boss and Zaneveld 2003). Due to its absorptive properties, CDOM protects marine organisms from UVR, and therefore has an important role in marine photochemical and photobiological processes (Nelson and Siegel 2002). Because exposure to high levels of UVR has been implicated in the bleaching of reef-building corals (Glynn 1996), temporal and spatial patterns of CDOM could explain local variations in coral bleaching intensity.

The focus of this study is to examine the transport of CDOM between shallow banks and deep basins in the Bahamas. The Bahama Archipelago consists of vast carbonate banks (average depth $\approx 3$ m) with islands, deep channels, and deep-water basins. The two basins, Tongue of the Ocean (TOTO) and Exuma Sound, are more than 1000 m deep and are mostly enclosed by islands and shallow-water banks. Shallow bank regions in the Bahamas are affected much more by latent and sensible heat fluxes to the atmosphere than are the deep basins, due to the limited heat capacity of a shallow water column (Smith 1995). The difference in response of these two regions to solar heating and evaporation acts to create density gradients between the banks and the deep basins (Smith 1995).

For this study, a location was selected near Lee Stocking Island (LSI) in the chain of Exuma Cays. This thin chain of islands separates Exuma Sound from the Great Bahama Bank. A one-year record of salinity and temperature from Adderly Inlet, a tidal channel adjacent to LSI, shows prominent temperature and salinity spikes from January through October. These spikes occur within each tidal cycle and represent warmer, more saline water leaving the banks during ebb tide in the summer months and cooler more saline water leaving the banks during the winter months (Smith 1995). During the spring
and summer, daytime heating may offset salinity effects on density, allowing some of the CDOM-rich water tidally advected into the sound to remain at the surface, where it can be sensed remotely. Wind forcing also plays a key role in determining both the steady and seasonally varying transport of salt, heat, and mass between the bank and basin regimes (Smith 1995). In this study, we used satellite ocean color data collected in deep water adjacent to LSI to examine the transport of water from the banks into the sound.

3.2 REMOTE SENSING

Most algorithms used to interpret ocean color measurements made from space involve taking spectral ratios of remote-sensing reflectance ($R_{rs} = \text{upwelling radiance}/\text{downwelling irradiance}$) to estimate chlorophyll concentration ([Chl]). The algorithm used in the Coastal Zone Color Scanner (CZCS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is based on the $R_{rs}(443\text{nm})/R_{rs}(550\text{nm})$ and $R_{rs}(490\text{nm})/R_{rs}(550\text{nm})$ ratios. However, these algorithms don’t take CDOM absorption into account, which can lead to significant errors in derived estimates of chlorophyll concentration (Carder et al. 1991). In order to try to estimate the absorption due to CDOM in surface waters, an algorithm is needed that can further spectrally decompose the radiance signal reaching the sensor.

One approach is to utilize a radiance band closer to the UV region of the spectrum. Such an algorithm has been developed for the Moderate Resolution Imaging Spectroradiometer (MODIS), which uses both the 412nm and the 443nm band in order to derive the absorption due to CDOM (Carder et al. 1999). This algorithm takes advantage of the fact that CDOM absorbs more strongly at 412nm than at 443nm, while phytoplankton absorbs more strongly at 443nm than at 412nm. Because the SeaWiFS
sensor also has a 412nm band, this algorithm can be applied to estimate CDOM absorption as well as chlorophyll concentration from SeaWiFS imagery. Recently, Hu et al. (2003) used this method to retrieve chlorophyll concentrations in the northeastern Gulf of Mexico by separating out the effects of CDOM absorption. The ability to estimate CDOM absorption using satellite data allows us to examine the export of material from the banks into deep basins throughout the Bahamas. Because reflected light from the shallow Bahamas Banks confounds algorithms used to estimate water-column properties (e.g., Lee et al. 1998), estimates of CDOM absorption from SeaWiFS data are only valid in deep water. By examining CDOM absorption in deep water adjacent to the banks, export from the banks can be inferred.

3.3 METHODS

Data for this study were collected around Lee Stocking Island in the Bahamas as part of the Coastal Benthic Optical Properties (CoBOP) experiment from 20 May until 3 June 1999 and from 17 May until 27 June 2000. Sampling locations included offshore sites in Exuma Sound, a tidal channel on the bank, and coral reef sites found on the narrow shelf separating the Exuma chain of islands from Exuma Sound (Fig. 3.1). Measurements of wind speed and direction were collected at a meteorological station located on LSI during the experiment.

Measurements of salinity as well as CDOM absorption ($a_{CDOM}$) were made using a slow-drop optical instrument package. This package was slightly negatively buoyant and was deployed so as to profile slowly through the water column to a maximum depth of approximately 70m. Instrumentation included a Falmouth Scientific Inc. 2” Micro-CTD (pressure, conductivity, and temperature), and two WET Labs, Inc. ac-9™
absorption meters (attenuation and absorption at wavelengths of 412, 440, 488, 510, 532, 555, 650, 676, and 715nm). One ac-9™ fitted with a 0.2 μm filter was used for dissolved absorption measurements. Data from the slow-drop instrument package were processed according to Ivey et al. (2002).

Figure 3.1 Satellite image and map of study area. A. Quasi true-color MODIS image of the Bahamas collected on March 14 2002. Shallow bank regions appear bright against the deep blue background. B. Map of study area. Sampling locations are denoted by black stars. Red square represents time-series location. Transect is given by red line. Numbered sampling locations represent stations shown in Figure 4.
During CoBOP 2000, transect measurements were made several times a minute by pumping near-surface sea water through a 120 liter insulated container while the ship was underway from Adderly Inlet to offshore sites in Exuma Sound (Fig.1). Immersed in the container were a Falmouth Scientific 2" MicroCTD, a WETLabs Flashlamp Fluorometer (CDOM fluorescence), and 3 WETLabs C-star transmissometers (488, 532, 660nm). During CoBOP 2000, seawater was pumped through the container at a rate of 17 to 25 liter per minute, providing a roughly five-minute flushing period.

SeaWiFS data (1km resolution) were processed to derive [Chl] and CDOM absorption using an algorithm developed by Carder et al. (1999), which can be parameterized for three bio-optical domains. For this study, the algorithm was tuned for an “unpackaged” regime, meaning an environment with a high fraction of photoprotective pigments and low self-shading by phytoplankton cells (Carder et al. 1999). This is appropriate for the clear waters of the Bahamas in the late spring. Level 1A SeaWiFS data collected by a High Resolution Picture Transmission receiving station located at the University of South Florida in St. Petersburg were processed on a Silicon Graphics workstation using the SeaWiFS Data Analysis System version 4.3.

Chlorophyll a concentrations used for comparison to satellite-derived values were determined fluorometrically (Holm-Hansen and Riemann 1978). Particulate absorption of surface water samples was determined using the quantitative filter pad technique (Truper and Yentsch 1967) with an optical pathlength elongation factor ($\beta$) as discussed in Carder et al. (1999).

Time series data collected during CoBOP 2000 in a tidally-flushed channel (Fig. 3.1) are provided by Emmanuel Boss and Ron Zaneveld (2003).
3.4 RESULTS AND DISCUSSION

The $a_{\text{CDOM}}(440)$-salinity relationship obtained from both bank and sound locations (Fig. 3.2) during CoBOP 1999 and 2000 is similar to that found in the same study area by Boss and Zaneveld (2003). The positive correlation between these two quantities suggests a common source location of CDOM and salinity. Negative correlations between the two would be expected if the source of CDOM was fresh water rich in CDOM, such as waters influenced by river runoff (e.g., Hu et al. 2003). In this area, however, with an absence of freshwater runoff, a positive correlation is consistent with our hypothesis that bank water is CDOM-rich and relatively saline-rich due to evaporation and primary production in the grass beds on the shallow banks. Warrior et al. (2002) show the effects of depth and bottom albedo on evaporation in the Bahamas, which result in enhanced salinity and density over the shallow banks.

Absorption, due to CDOM and particulates, and salinity are both much higher on the banks than in Exuma Sound (Table 3.1). The gradient between the two regions can also be easily seen in the transect data collected during CoBOP 2000 (Fig. 3.3). As the ship moved away from the banks, values of beam attenuation and relative CDOM fluorescence all decreased. Boss and Zaneveld (2003) found that bank regions, particularly reefs and seagrass beds, are sources of colored dissolved material, which is consistent with our findings.
Figure 3.2 Relationship between salinity and CDOM absorption. Both bank and sound locations during CoBOP 1999 and 2000 are shown. Boss (2003) data were collected inshore near corals, sand, and grass beds during CoBOP 2000.

Table 3.1 Comparison of surface measurements of $a_{CDOM}(440)$, $a_p(440)$, salinity, and the ratio $a_{CDOM}(440)/a_p(440)$ at locations on and off the Bahamas Banks.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{CDOM}(440)$</td>
<td>banks</td>
<td>0.0429</td>
<td>0.0742</td>
<td>0.0586</td>
</tr>
<tr>
<td></td>
<td>offshore</td>
<td>0.0141</td>
<td>0.0615</td>
<td>0.0302</td>
</tr>
<tr>
<td>$a_p(440)$</td>
<td>banks</td>
<td>0.0064</td>
<td>0.018</td>
<td>0.0137</td>
</tr>
<tr>
<td></td>
<td>offshore</td>
<td>0.0031</td>
<td>0.0182</td>
<td>0.0073</td>
</tr>
<tr>
<td>Salinity</td>
<td>banks</td>
<td>37.01</td>
<td>37.56</td>
<td>37.18</td>
</tr>
<tr>
<td></td>
<td>offshore</td>
<td>36.78</td>
<td>37.2</td>
<td>37.04</td>
</tr>
<tr>
<td>$a_{CDOM}(440)/a_p(440)$</td>
<td>banks</td>
<td>1.406</td>
<td>4.122</td>
<td>2.212</td>
</tr>
<tr>
<td></td>
<td>offshore</td>
<td>0.758</td>
<td>1.990</td>
<td>1.231</td>
</tr>
</tbody>
</table>
Figure 3.3 Transect measurements made while underway from the Bahamas Banks into Exuma Sound. Beam attenuation at 488nm (c488), 532nm (c532), and 660nm (c660) as well as CDOM fluorescence all decreased as the ship moved east, away from the banks.

The absorption properties of the study area are dominated by dissolved material as seen in the ratios of dissolved absorption to particulate absorption \( \frac{a_{CDOM(440)}}{a_p(440)} \) (Table 3.1). Values of this ratio range from 1.4 to more than 4 on the banks, while in Exuma Sound the range was from 0.76 to around 2. These values are much greater than ranges reported in a Morel Case 1 environment like the Gulf of Mexico, which are 0.3 to 0.7 (Walsh et al. 1992). Only in the clearest offshore waters of Exuma Sound could Case 1 waters be found.

Time-series data collected just to the north of LSI in a tidally-flushed channel (Fig. 3.1) show tidal fluctuations of water depth, temperature, salinity, density, and CDOM absorption (Fig. 3.4). As water depth increases on the flood tide, salinity and
CDOM absorption decrease. On the ebb tide, as bank water is pushed into the sound, salinity and CDOM absorption levels in the tidal channel increase. Data from this time-series is consistent with our data, suggesting that water from the banks is rich in CDOM and relatively saline when compared to water from Exuma Sound.

Warmer daytime temperatures created on the banks by solar heating are seen during the ebb tide at around 4:00 p.m. on May 20 (Fig. 3.4). On the following ebb tide around 6:00 a.m., however, no temperature increase is seen, consistent with the lack of heating during nighttime hours. On afternoon ebb tides, warmer temperatures associated with elevated salinities can create water that is less dense and likely to remain at the surface, while morning ebb tides, with low temperatures and elevated salinities, create dense water that is likely to sink as it moves away from the banks.

For example, water from the morning ebb tide in Figure 4C, with a sigma-t value of around 24.95 kg/m³, has an ambient depth in Exuma Sound of around 40 m (Fig. 5C), while less dense water from the ebb tide the following afternoon (sigma-t ≅ 24.5) has an ambient depth near the surface (Fig. 3.5C). Because plumes have been found to entrain ambient sound water as they cascade over the shelf break (Hickey et al. 2000), this dense water from the morning ebb tide would reach a depth somewhat less than 40 m. On the next ebb tide on the afternoon of May 21, however, water forced into the sound would remain at the surface.
Figure 3.4 Time-series data collected during CoBOP 2000 on the banks in a tidally-flushed channel. Data courtesy of Boss and Zaneveld (2003). Solid line in each plot represents water depth(m). Dashed lines represent salinity (A), temperature (B), sigma-t (C), and CDOM absorption at 440nm ($a_g(440)$) (D).
A recent study of this region found that as these plumes leave the banks and cascade over the narrow shelf, they entrain ambient mixed-layer water of Exuma Sound and descend to the base of the mixed layer, where they can subsequently spread along isopycnals tens of kilometers into the sound (Hickey et al. 2000). Observed plume depths in November averaged 75m, while the June plumes were observed at shallower depths (~45m), consistent with shallower mixed-layer depths observed during the summer months. Subsurface salinity maxima were often associated with minima in percent light transmission, indicating a shallow-water, sedimented origin of plume water (Hickey et al. 2000).

Vertical profiles of temperature, salinity, sigma-t, and $a_{CDOM}(440)$ collected during CoBOP 1999 are shown in Figure 3.5. In Figure 5D, the variability in $a_{CDOM}(440)$ measurements of surface waters is high. CDOM absorption typically reaches a minima at the bottom of the mixed layer and then increases with depth. Mixed-layer depths of around 20m down to 45m are consistent with summertime salinity maxima found by Hickey et al. (2000) in Exuma Sound. The fact that these surface plumes involve not only increased temperature and salinity, but also $a_{CDOM}(440)$, points to a saline, CDOM-rich origin, such as the shallow banks.
Figure 3.5 Profiles of salinity (A), temperature (B), sigma-t (C), and $a_{CDOM(440)}$ (D) vs. depth for three sampling days during the CoBOP 1999 Experiment.
The role that wind forcing plays in the exchange of water between the banks and the deep basins can be examined here using depth profiles collected during CoBOP 1999 in Exuma Sound before and after a wind event (Fig. 3.6). During the wind event, wind speeds increased from approximately 4 m/s to around 6 m/s between May 30 and June 3, and wind direction changed from around 50 degrees (NE winds) to around 100 degrees (ESE winds), impacting on a SE-NW trending coastline. Figure 3.6 shows $a_\phi(440)$ vs. sigma-t before (May 24) and after (June 3) the wind event. Prior to the wind event, onshore NE winds suppressed offshore flow of water from the banks, and a sigma-t value of around 24.5 kg/m$^3$ represents a minima in $a_{CDOM}(440)$. After the wind event, a similar sigma-t value represents a maximum in $a_{CDOM}(440)$. This suggests that ESE winds forced CDOM-rich water from the banks and seagrass beds into Exuma Sound. High CDOM absorption was found with sigma-t values as high as 24.6 kg/m$^3$ on June 6 1999, consistent with an ambient depth of about 25m.
Figure 3.6 Plots of $a_{CDOM}(440)$ vs. sigma-t for all depths from two different profiles. The dotted profile was sampled prior to a wind event, while the solid profile was sampled after winds increased from 4m/s to 6m/s and changed from NE to ESE. Both sites are offshore in Exuma Sound.

Figure 3.7 shows SeaWiFS images from 1999, covering Exuma Sound and TOTO, processed using the MODIS algorithm (Carder et al. 1999) to derive $a_{CDOM}(400)$ values. To allow comparison to Table 3.1, values of $a_{CDOM}(400)$ can be divided by 1.4 to estimate the $a_{CDOM}$ value at 440nm. This is because the spectral absorption of CDOM can be fit to the form $a_g(\lambda) \sim a_g(400)e^{-S(\lambda-400)}$ (Roesler et al. 1989), where $S = 0.012$ is the spectral slope measured in Exuma Sound near LSI. Throughout the year, overall $a_{CDOM}(400)$ levels in TOTO are roughly double those in Exuma Sound. Levels of $a_{CDOM}(400)$ in both of these deep basins are significantly elevated compared to levels in
the eastern edge of the Atlantic Ocean (NE portion of each image). The wintertime image (Fig. 3.7A) shows uniform $a_{CDOM}(400)$ levels in TOTO and Exuma Sound. During the spring, summer, and fall, plumes rich in CDOM can be observed along the margins of both deep basins. In particular, the northern portion of Exuma Sound, which has no islands to contain water on the banks, has visible plumes in all but the wintertime image. The image from May 26th (Fig. 3.7D), collected during the CoBOP 1999 experiment, shows a distinct plume extending offshore from just south of LSI. Once in the sound, the plume is seen moving in a northwesterly direction, which is consistent with observed surface currents in Exuma Sound (Colin 1995).

SeaWiFS data processed using the Ocean Color 4 (OC4) algorithm (O’Reilly et al. 1998) to derive chlorophyll concentrations produced erroneously high estimates. When the image from May 26th, 1999 (Fig. 3.7D), collected during CoBOP 1999, was processed with the SeaWiFS OC4 chlorophyll algorithm, chlorophyll estimates in the plume seen extending off the banks near LSI in figure 3.7D were about 0.17mg/m$^3$. Using the Carder MODIS algorithm instead produced chlorophyll estimates of around 0.11mg/m$^3$. This value is much closer to the value of 0.08mg m$^{-3}$ measured in the sound at the same site on the day of the image. Satellite-derived estimates of CDOM absorption in the same plume were on the order of 0.025m$^{-1}$ at 440nm, which compare well to the measured value of 0.03m$^{-1}$ at 440nm. By applying the Carder MODIS algorithm to SeaWiFS data, CDOM absorption is separated from phytoplankton absorption using the spectral differences between these components, providing chlorophyll estimates not contaminated by CDOM absorption.
Figure 3.7 SeaWiFS imagery of the Bahamas during 1999. All images were processed to derive absorption by CDOM at 400nm using MODIS semi-analytical algorithm (Carder et al. 1999). The 26 May image (D) was collected during the CoBOP 1999 experiment and shows a distinct plume, rich in CDOM, originating on the banks just to the south of LSI (green arrow).
One potential ecological impact of CDOM transport between the Bahamas Banks and the surrounding deep basins is on coral reefs that lie along the margin between the two regimes. Coral bleaching, the temporary or permanent loss of endosymbiotic algae (zooxanthellae) and/or their photosynthetic pigments, has been linked to elevated seawater temperatures as well as UV radiation (Glynn 1996). Coral reefs are present throughout the Exuma chain, consisting mainly of fringing reefs, located along the eastern margin of the Exuma chain, and channel reefs that are located in tidal channels between the banks and Exuma Sound (Chiappone et al. 1997). Coral bleaching was documented near LSI as part of a widespread bleaching event in the Western Atlantic during the last half of 1987, and prolonged contact with warm, saline plumes originating on the banks and flowing out into Exuma Sound was hypothesized to be the cause (Lang et al. 1988). In addition, scleractinian corals in the area were found to be disproportionately affected on their upward-facing surfaces, indicating that exposure to solar radiation may have played a role in the onset of bleaching (Lang et al. 1988).

To estimate the impact that transport of CDOM over coral reefs might have on the underwater light field, Hydrolight© (Mobley 1994) simulations were carried out to estimate the total absorption budget for the region and the spectral diffuse attenuation coefficient for downwelling light \( (K_d(\lambda)) \). Hydrolight-derived \( K_d \)’s were then extrapolated to 300nm using the slope of the CDOM absorption spectrum. Downwelling solar irradiance was measured on land during CoBOP 1999 and 2000 using a LI-COR LI1800 spectroradiometer. Using the calculated \( K_d \)’s and the measured surface spectral downwelling irradiance \( (E_d) \), irradiance spectra at depth were calculated based on the following equation:
\[ E_d(\lambda,z) = E_d(\lambda,0^+) \cdot e^{-K_d(\lambda)z} \] (3.1)

\[ E_d(\lambda,z) \] is the spectral downwelling irradiance at depth \((z)\). \(E_d(\lambda,0^+)\) is the spectral downwelling irradiance just below the sea surface.

**Table 3.2** Input parameters for Hydrolight© simulations.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Ebb tide case (bank water)</th>
<th>Flood tide case (sound water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDOM absorption (a_{\text{CDOM}}(440\text{nm}))</td>
<td>0.06 m(^{-1})</td>
<td>0.02 m(^{-1})</td>
</tr>
<tr>
<td>Chlorophyll concentration [Chl]</td>
<td>0.12 mg m(^{-3})</td>
<td>0.06 mg m(^{-3})</td>
</tr>
<tr>
<td>CDOM spectral slope</td>
<td>0.012</td>
<td>0.009</td>
</tr>
<tr>
<td>Solar zenith angle</td>
<td>3.0 Degrees</td>
<td>3.0 Degrees</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>1 m/s</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Cloud %</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Backscatter fraction</td>
<td>0.015</td>
<td>0.015</td>
</tr>
</tbody>
</table>

For the ebb-tide case, when bank water flows into Exuma Sound, bank water conditions were used. Sound water conditions were used to simulate the flood-tide case when sound water extends onto the bank. Input parameters for the Hydrolight© simulations for ebb- and flood-tide cases are given in Table 3.2. The contributions of minerals, CDOM fluorescence, chlorophyll fluorescence, and Raman scattering were not included as part of the simulations. Values of \(a_{\text{CDOM}}\) and [Chl] used in simulations were approximate mean values for bank and sound water determined experimentally during the
CoBOP 1999 and 2000 experiments. The influence of bottom reflectance was included in irradiance estimates by assuming a coral-sand bottom, however, bottom reflectance had a negligible effect on downwelling irradiance.

Hydrolight© simulations of the water column absorption budget during ebb tide (bank water) are given in Figure 3.8. In the UV and blue regions of the spectrum ($\lambda \leq 450\text{nm}$), absorption by CDOM dominates the total absorption budget. This is consistent with the measured ratios of dissolved to particulate absorption seen in Table 3.1 and validates our use of the CDOM absorption slope to extrapolate $K_d$ values from 360nm to 300nm. The Hydrolight©-derived $K_d$ spectra and associated $E_d$ spectra at 5m for both ebb and flood tide cases are shown in Figure 3.9. $K_d$ values simulated by Hydrolight© and extrapolated to 300nm are consistent with $K_d$ values over reefs near LSI measured by Lesser et al. (2001).

Figure 3.8 Hydrolight©-simulated absorption budget for Exuma Sound. In the ultraviolet and blue regions of the spectrum, total absorption is dominated by CDOM.
To estimate potential doses of DNA-damaging UVR, downwelling irradiance at depth was weighted using a spectral response function developed by Setlow to assess which wavelengths of UVR cause the most damage to DNA (inset, Fig. 3.10) (Setlow 1974). Dose rate estimates of harmful UVR under flood tide conditions at a depth of 5m reach a maximum of around $3 \times 10^{-4}$ (relative response) at 304nm (Fig. 3.10). Under ebb tide conditions, with increased CDOM absorption, the dose rate at 304nm is approximately one-fourth of the flood tide estimate. These estimates for the Bahamas are much higher than maximum dose rates estimated in the Florida Keys ($\sim 10^{-5}$) (Anderson et al. 2001) and slightly higher than those found in the Maldives ($\sim 10^{-5}$) (Dunne and Brown 1995). In the Florida Keys study, dose rate estimates at 3-4m depth at 304nm were between 25 to 35% of the surface value. Under flood tide conditions, dose rate
estimates at 5m from this study are around 50% of surface values, while during ebb tide, the value drops to around 12% (Table 3.3). These data indicate that waters surrounding LSI are very clear, and corals in this region can be exposed to high levels of DNA-damaging radiation if they grow as shallow as 5m. Relative dose rate levels at 304nm as a percentage of the surface dose rate at three different depths (5,10,15m) under ebb and flood tide conditions are given in Table 3.3 for comparison.

Plumes flowing off the banks and into Exuma Sound are important to reefs not only as warm, saline water source which may expose corals to temperature and salinity extremes, but also because the associated dissolved material has the ability to protect corals from UV and visible radiation.

![Figure 3.10](image)

**Figure 3.10** Dose rates estimated at 5m and at the surface by weighting the downwelling irradiance by the action spectrum for DNA damage (Setlow 1974). Inset: Setlow action spectrum for DNA damage (Setlow 1974). X-axis is wavelength(nm) and y-axis is relative response.
### Table 3.3 Percentage of surface dose rate at different depths for ebb and flood tide cases.

<table>
<thead>
<tr>
<th>Region</th>
<th>Ebb</th>
<th></th>
<th></th>
<th></th>
<th>Flood</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>5m</td>
<td>10m</td>
<td>15m</td>
<td>5m</td>
<td>10m</td>
<td>15m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of surface dose rate</td>
<td>12.0%</td>
<td>1.4%</td>
<td>0.2%</td>
<td>49.2%</td>
<td>24.2%</td>
<td>11.9%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.5 CONCLUSIONS

The optical properties of the environment surrounding Lee Stocking Island are dominated by dissolved substances. Boss and Zaneveld (2003) showed that on the banks, absorption due to CDOM was higher closer to the bottom, indicating seagrass beds, reefs, and benthic organisms living in and on bank sediments are a source of CDOM. Coastal depth profiles exhibiting surface maxima in salinity, and CDOM absorption suggest that water from the Bahamas Banks flows offshore into Exuma Sound. Density fluctuations on the banks associated with solar heating and evaporation cycles will have a large impact on whether plumes remain at the surface or sink to depth. CDOM contained in dense plumes which sink to depth will be exposed to less light at depth with less chance of being photo-oxidized. Both the CDOM-rich, saline plumes found at depth and those that remain on the surface observed in SeaWiFS imagery are hypothesized to be the result of a Bahamas Banks source with shallow-water evaporation, followed by tidal and wind advection into deeper water. Water exported at the end of a solar heating cycle can be buoyant enough to remain at the surface offshore, while water exported at the end of a nocturnal cooling period likely dominates the plumes found at depth. From SeaWiFS imagery, we can observe that plumes of CDOM-rich water produced on the Bahamas banks flow out into both TOTO and Exuma Sound at various times throughout the year.
Because wind forcing plays a large role in the transport of material from the banks into deep basins, plume development is variable. CDOM transported from the banks, over coral reefs, and into deep basins affects the underwater light field by absorbing UVR and cutting the level of damaging radiation to which reefs are exposed. Future work in this area will include further studies of seasonal and annual variations in the development of CDOM-rich plumes in the Bahamas and other coral reef areas throughout the world.
4. SPATIAL AND TEMPORAL VARIABILITY OF OCEAN COLOR PARAMETERS IN CORAL REEF REGIONS

4.1 INTRODUCTION

In this chapter, time series analyses of remotely-sensed ocean color parameters in coral reef regions throughout the world will be presented. Although coral reefs are generally found in clear, nutrient-poor waters, optical properties of the water column in reef regions are highly variable in terms of levels of light-absorbing constituents, such as CDOM and pigmented particles containing chlorophyll. Concentrations of light-absorbing constituents vary in space and time. This variability will be examined both within individual reef regions and between regions. Finally, a set of simulations of underwater irradiances to which coral reefs are exposed will be presented.

4.1.1 Coral Reefs

Reefs have occurred intermittently over the past several hundred million years and much evidence of their history can be found in the fossil record (Pandolfi 2011). Within the larger group of cnidarians known as corals, one particular group, hermatypic corals of the Order Scleractinia, are calcifying organisms which remove calcium from the water column and incorporate it into their skeletons in the form of calcium carbonate. Over time, reef-building corals can build large reef structures as dead coral skeletons
form a foundation and provide substrate for living coral tissue and a diverse community of associated organisms.

Reef-building corals are able to thrive in clear, nutrient-poor waters due to zooxanthellae, which are endosymbiotic algae that live within coral tissues and harvest energy contained in sunlight. By utilizing energy from sunlight and carrying out photosynthesis, zooxanthellae provide coral hosts with up to 95% of their energy requirements (Hallock 1981, Dubinsky and Falkowski 2011, many others). This close symbiotic relationship between a primary producer and a consumer allows for high levels of nutrient recycling between the two organisms and is the reason behind the high productivity of coral reefs (Hallock 1981, Hoegh-Guldberg 1999, many others).

The distribution and growth of coral reefs throughout the world is determined by environmental factors, which include water temperature, wave energy, light, water quality, tidal regime, salinity, and turbidity (Pandolfi 2011). Because algal symbionts rely on sunlight to synthesize organic compounds, the underwater light field incident upon coral reefs is very important. Light penetration determines the depth to which corals can survive and construct a reef framework. Most coral reef growth is limited to the upper 100m of the water column in very clear waters and shallower depths in more turbid waters. Corals, even some with algal symbionts, can thrive at deeper depths, but do not build reefs (Dubinsky and Falkowski 2011).

In addition to determining the depths to which reef-building corals can exist, the underwater light field has a strong influence on coral pigmentation. Photoacclimation of zooxanthellae results in differences in pigmentation when comparing deep-water versus shallow-water corals. For example, in the Red Sea coral *Stylophora pistillata*, shallow-
water colonies have tissues which are nearly transparent, while conspecific colonies from deep water are much more highly pigmented (Dubinsky et al. 1984). This photoacclimation results from the fact that corals in deep water receive much less light than those near the surface and have high pigment densities in order to absorb as much available sunlight as possible. Conversely, corals in shallow water are exposed to much more light than is required for photosynthesis and have low pigment densities, allowing the coral skeleton to reflect sunlight. Shallow-water corals must in fact utilize mechanisms to quench reactive oxygen species (ROS) produced by the splitting of water during photosynthesis (Levy et al. 2006a,b). Overall, it is estimated that deep-water corals absorb nearly 100% of incident light while shallow-water corals absorb less than 10% (Stambler and Dubinsky 2005).

The morphology of coral colonies is also affected by the underwater light field. Colonies of the Hawaiian coral Montipora verrucosa exhibit different colony architecture based on depth. Colonies near the surface are profusely branched with a more vertical orientation. Deep-water colonies, rather, exhibit less branching and have a more horizontal orientation to maximize light absorption (Dubinsky and Falkowski 2011).

Another effect that the underwater light field has on coral reefs is on nutritional status. Due to lower light levels, algal symbionts in deep-water corals cannot produce enough photosynthate to meet the energy requirements of their hosts. Deep-water coral hosts must rely on the capture of zooplankton to fulfill their energy needs. Zooxanthellae in shallow-water corals produce abundant energy for their hosts, but become limited in terms of nitrogen and phosphorous due to the oligotrophic nature of the surrounding waters. Shallow-water corals depend on predation of zooplankton for additional nutrients.
to fuel growth, despite the high rate of photosynthesis in the high-light regime in which they live (Dubinsky and Falkowski 2011).

Coral reefs are currently threatened by a number of factors which are anthropogenic in origin. Some of these threats are due to direct human activity at reef sites themselves, such as coastal development, eutrophication, overfishing, and sedimentation. Threats related to climate change are less direct, but occur on a global scale and are due in part to greenhouse gas emissions into the atmosphere. The two main threats in this category are warmer seawater temperatures as well as increased acidity (lower pH) of oceans worldwide. Mass bleaching episodes are triggered by photo-oxidative stress and elevated seawater temperatures, which will be discussed in Chapter 5. Ocean acidification, due to an accumulation of dissolved carbon dioxide in oceans worldwide, reduces the concentration of carbonate ions, required by corals and other calcifying organisms to build skeletons and shells, and is a threat which may nearly wipe out coral reefs entirely if emission levels of greenhouse gases into the atmosphere continue in a "business as usual" manner (Hough-Guldberg et al. 2007).

4.1.2 Coral reef regions examined in this study

Coral reef regions selected for examination in this study were chosen to represent a sampling of coral reef regions throughout the world. The main selection criteria were reef regions that have been well-studied, including published studies of optical property measurements, the presence of bleaching observations and reports of bleaching patterns found in the scientific literature. The Great Barrier Reef (GBR), for example, is a very large area that has been extensively researched with an extensive set of bleaching observations, not only indicating reefs that bleached during a particular time period, but
also reefs that did not bleach. Coral reefs in Thailand are not as numerous as those on the GBR, but have been the focus of many studies in the scientific literature, particularly reefs near Phuket, which thrive despite turbid water conditions. In the following sections, reef regions examined in this study will be described, including previous studies found in the scientific literature and other characteristics which make them worthy of examination. Observed bleaching episodes in these reef regions will be described in Chapter 5.

Coral reef regions examined in this study are listed in Table 4.1. Four maps of the study areas are also shown in Figures 4.1 (Great Barrier Reef), 4.2 (Southeast Asia), 4.3 (Indian Ocean) and 4.4 (Western Atlantic Ocean and Caribbean Sea). In Figures 4.1-4.4 red text indicates ROI names corresponding to Table 4.1. Hatched regions in black indicate the spatial extent of processed satellite imagery.
Table 4.1 Regions of interest (ROIs) examined in this study

<table>
<thead>
<tr>
<th>ROI abbreviation</th>
<th>ROI name</th>
<th>Boundaries (deg. latitude, deg. longitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAH A</td>
<td>Bahamas</td>
<td>22.54°N - 27.50°N, 79.75°W - 72.95°W</td>
</tr>
<tr>
<td>BALI</td>
<td>Island of Bali (Indonesia)</td>
<td>9.53°S - 6.50°S, 113.5°E - 117.35°E</td>
</tr>
<tr>
<td>GBRn</td>
<td>Great Barrier Reef north</td>
<td>10.25°S - 15.23°S, 142.50°E - 148.90°E</td>
</tr>
<tr>
<td>GBRc</td>
<td>Great Barrier Reef central</td>
<td>15.23°S - 20.21°S, 145.01°E - 151.53°E</td>
</tr>
<tr>
<td>GBRs</td>
<td>Great Barrier Reef south</td>
<td>20.21°S - 25.19°S, 148.01°E - 154.71°E</td>
</tr>
<tr>
<td>KEYS</td>
<td>Florida Keys</td>
<td>23.48°N - 26.5°N, 83.5°W - 79.34°W</td>
</tr>
<tr>
<td>MALD</td>
<td>Maldives Islands</td>
<td>2.48°N - 5.50°N, 71.0°E - 74.84°E</td>
</tr>
<tr>
<td>PALA</td>
<td>Palau</td>
<td>5.98°N - 9.0°N, 132.5°E - 136.34°E</td>
</tr>
<tr>
<td>PANA</td>
<td>Panama</td>
<td>5.53°N - 10.5°N, 84.0°W - 77.69°W</td>
</tr>
<tr>
<td>PHIn</td>
<td>Philippines north</td>
<td>11.68°N - 16.65°N, 119.0°E - 125.43°E</td>
</tr>
<tr>
<td>PHIc</td>
<td>Philippines central</td>
<td>6.75°N - 11.75°N, 118.0°E - 124.33°E</td>
</tr>
<tr>
<td>PHPe</td>
<td>Philippines east</td>
<td>8.98°N - 12.0°N, 123.0°E - 126.85°E</td>
</tr>
<tr>
<td>PHIs</td>
<td>Philippines south</td>
<td>4.47°N - 7.50°N, 122.2°E - 126.04°E</td>
</tr>
<tr>
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<td>Thailand north</td>
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</tr>
<tr>
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<td>Thailand central</td>
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</tr>
<tr>
<td>THAs</td>
<td>Thailand south</td>
<td>0.55°N - 5.51°N, 100.0°E - 106.29°E</td>
</tr>
<tr>
<td>YAP</td>
<td>Yap Island</td>
<td>7.97°N - 11.0°N, 136.0°E - 139.86°E</td>
</tr>
</tbody>
</table>

Figure 4.1 Regions of interest located on the Great Barrier Reef. Hatched regions indicate where satellite imagery was processed. ROI abbreviations in red correspond to Table 4.1.
Figure 4.2 Regions of interest in southeast Asia.

Figure 4.3 The Maldives region of interest (MALD) located in the Indian Ocean.
The following sections contain brief descriptions of the physical setting and oceanographic conditions found in each region. Descriptions of bleaching episodes observed in these regions can be found in Chapter 5.

4.1.2.1 Great Barrier Reef

The Great Barrier Reef (GBR) is located along the eastern Australian coast and extends approximately 2600km from 25°S to just north of 10°S. Rather than a continuous barrier, the GBR is actually a matrix of more than 2800 individual reefs that range in size...
from 0.01 to 100km² (Wolanski 2001). Channels formed by inter-reefal waters flow between the individual reefs and range from several hundred meters to tens of kilometers wide. This matrix of reefs and inter-reefal waters lies on the continental shelf, which drops off into the Coral Sea to the east. The continental shelf and reef matrix are quite narrow in the northern GBR and gradually widen, reaching their widest point around 22.5°S. Figure 4.5 depicts the matrix of reefs in the GBR. Water depths on the shelf range from just a few meters near the coast to around 40-50 meters in the lagoon between the coast and the reef matrix, to 80-100 meters near the shelf break. East of the shelf break, depth increases rapidly to more than 4000m in the Coral Sea. Fringing reefs close to shore on the GBR will not be considered in this study because shallow water depths make remotely-sensed retrievals of water-column optical properties impossible. The matrix of reefs and inter-reef channels is not consistent along the length of the GBR. Some areas have low reef density, where reefs block around 10% of the length along the shelf, while other areas contain a high density of reefs and cover almost 90% of the length (Spagnol et al. 2001).

Rainfall on the GBR occurs mostly during the austral summer (December-February), when temperatures are maximal. Although general patterns in terms of wet and dry seasons are consistent throughout the length of the GBR, there are differences. The wet tropics are found at the north end of the central GBR, where rainfall is high and conditions are generally warm and humid. Several rivers drain into the GBR here, including the Murray, Tully, Johnstone, Mulgrave-Russel, Mossman and Daintree (Furnas 2003).
Figure 4.5 The matrix of reefs that form the Great Barrier Reef. Reefs are shown in pink and mangroves in green. The bifurcation of the South Equatorial Current (SEC) into the East Australian Current (EAC) and Hiri Current occurs between 14°S and 18°S.

Water circulation on the GBR is influenced by winds, tides, and currents. Tidal currents move back and forth across the continental shelf and are the primary drivers of day-to-day water movement in the GBR (Furnas 2003). Tides in the northern and central GBR have a range of 3-5m, while in the southern GBR the tidal range is greater, from 5-8m (Hopley 2007). The South Equatorial Current (SEC) flows west and collides with the Australian continent between 14°S and 18°S, causing a deflection and bifurcation of the SEC into two western boundary currents, one flowing northward, the Hiri Current, and
one flowing southward, the East Australian Current (EAC) (Church 1987) as shown in Figure 4.5. North of this bifurcation, the weakly flowing Hiri Current does not penetrate the dense reef matrix and longshore flows are minimal (Furnas 2003).

South of the bifurcation, the bulk of the EAC flows eastward of the continental shelf, while a portion of it enters the reef matrix south of 17°S, causing a residual southward flow in the lagoon. However, this southward flow is opposed by the southeasterly trade winds, which can create a two-layered flow pattern in outer shelf waters, with wind-forced northward surface flow overlying southward moving deeper water (Furnas 2003). Near the coast, the influence of winds extends to the bottom and leads to the formation of a northward-flowing current along the coast. The interaction of the coastal current and the two layered system of the lagoon and outer shelf creates a front between coastal waters and those found in the lagoon, which acts as a barrier to the mixing of coastal waters with water in the lagoon (Furnas 2003). This front, or shear zone, is dependent on the strength of the southeasterly winds and may disappear during times of low southerly wind stress. The main consequence of the presence of a shear zone is that water from river plumes may become trapped in the coastal current and transported northward with limited mixing with water in the lagoon (Furnas 2003). A study by Choukroun et al. (2010) found that daily water exchange between the Coral Sea and GBR (~23km³/day) was as large as the average annual input of river water into the GBR (~26km³/year), indicating that in the reef matrix and lagoon, water exchange with the Coral Sea is of much higher importance than river input. Residence times for water in the GBR were found to be on the order of a few weeks.
4.2.1.2 Thailand

Reefs in Thailand are located on both sides of the Thai peninsula, with coastal margins on the Andaman Sea and the Gulf of Thailand. A map of the area showing the locations of reefs and mangroves is shown in Fig. 4.6. Climate and circulation patterns as well as reef development in both the Gulf of Thailand and Andaman Sea are heavily influenced by the Asian Monsoon, which is the dominant weather pattern in southeast Asia and the Indian Ocean. The monsoon has two main phases, the southwest monsoon, from May until October, where a warming Asian continent drives a massive seabreeze, bringing warm, moist air to Asia from the Indian Ocean, Andaman Sea, Gulf of Thailand, and South China Sea. During the months of November through April, the Asian continent cools and the northeast monsoon brings cooler dry air to India and southeast Asia (Frater 2005).

The Gulf of Thailand is a shallow enclosed sea with water depths generally less than 60m. Heavily sedimented, the Gulf of Thailand is a harsh environment for coral reefs, with most reef formation occurring on offshore islands, away from riverine input (Spalding et al. 2001). The Gulf of Thailand is under intense development pressure, mainly from agriculture and aquaculture, and 80% to 90% of mangrove forests in the Gulf of Thailand have been lost over the last 30 years, leading to increased sedimentation (Giri et al. 2008, Thampanya et al. 2006). Circulation in the Gulf of Thailand is dependent on the monsoon, with counter-clockwise circulation during the southwest monsoon and clockwise circulation in the Gulf during the northeast monsoon (Idris and Mohd 2007).
A somewhat different environment is found on the the Thai coast of the Andaman Sea, with the largest areas of mangrove forest in Thailand (Giri et al. 2008) and reefs exposed to onshore winds and rough conditions during the southwest monsoon and calm conditions during the northeast monsoon (Spalding et al. 2001). Reef development tends to be related to distance from shore and level of exposure to harsh sea conditions to the west, with the most developed reefs found on the eastern coasts of offshore islands (Spalding et al. 2001).

Figure 4.6 Reef locations in the Andaman Sea and western Gulf of Thailand. Reefs are in orange and mangroves in green.
4.2.1.3 Bali

The island of Bali is part of Indonesia, located off the eastern end of the island of Java. The location of reefs and mangroves near Bali is shown in Figure 4.7. The Lombok Strait lies between the islands of Bali and Lombok and is part of the Indonesian Throughflow (ITF), a circulation pattern set up by water from the Pacific Ocean flowing southward east of the island of Borneo and then into the Indian Ocean through one of two straits, The Timor Passage and the Lombok Strait (Sprintall et al. 2009), shown by the black arrows in Figure 4.7. Climate and the strength of the ITF here depend on the Asian monsoon, with the ITF at a maximum during the southwest monsoon in summer. During the northeast monsoon, surface flow reverses weakly through the Lombok Strait (Sprintall et al. 2009). Air temperatures are nearly constant throughout the year, but due to humid air deflected over the region by the island of Sumatra during the northeast monsoon, the wet season occurs during the winter months, while the dry season is in summer (Spalding et al. 2001).
4.2.1.4 The Philippines

The Philippines are located in an area in southeast Asia called the coral triangle that is home to the greatest concentration of reef biodiversity on Earth. Reefs in several countries make up the coral triangle, including the Philippines, Indonesia, and Malaysia. Figure 4.8 shows the locations of reefs and mangroves in the Philippines. The country is a large complex mass of islands that is home to vast reef areas. Climate and ocean circulation in the Philippines are influenced by the monsoonal weather pattern and two large bodies of water that border the islands to the east and west, the South China Sea and
the Pacific Ocean. On the western side of the archipelago, bordering the South China Sea, maximal rainfall is from July through August, while on the Pacific side, rainfall is maximal from October to January (Pajuelas 2000). The North Equatorial Current (NEC) flows into the archipelago and splits into a northward-flowing current that becomes the Kuroshio Current and the southward-flowing Mindanao Current as shown in Figure 4.7 (Spalding et al. 2001). Surface flow is generally into the Sulu Sea from the South China Sea to the north and the Pacific Ocean to the east, although current reversals in the Bohol and Sibuyan Seas occur during the summer (southwest monsoon), as shown with white arrows in Figure 4.8. Water exiting the Sulu Sea flows south and into the Celebes Sea (Han et al. 2009).
4.2.1.5 The Islands of Palau and Yap

Palau and Yap are isolated island arcs located east of the Philippines in the western Pacific Ocean. Palau contains several islands and is itself a country, the Republic of Palau, while Yap has a single main island and is one of the Federated States of Micronesia. Figure 4.9 shows the locations of the two island arcs and their reefs along with surface circulation features. The reason for their inclusion in this study, as mentioned in Chapter 1, is that while the two island arcs are similar in terms of size and
their remote open ocean location, they are very different in terms of their mangrove communities. Mangrove communities on Yap are well-developed, while mangroves on Palau are smaller and limited to the center of the main island, away from the barrier reefs (Spalding et al. 2001). Both islands have well-developed barrier reefs which surround the islands.

Palau and Yap lie in an area in the western Pacific with very dynamic ocean currents (Colin 2009). Surface currents near the two islands are driven by large-scale circulation features and follow the seasonal pattern of the Asian monsoon (Heron et al. 2006). During the winter, northward circulation around both Palau and Yap is driven by the Mindanao Eddy (ME), which results from a bifurcation in the North Equatorial Current (NEC). In the summer, a small eddy forms to the east of Palau called the Palau Eddy (PE), which changes the flow southward east of Palau. This seasonal eddy is smaller and weaker than the Mindanao Eddy, but affects the surface circulation near both sets of islands (Heron et al. 2006). While the current regime surrounding the islands is very dynamic, it has been observed that the waters around Palau are a mixture of both local waters and oceanic waters, with elevated nutrient and and larvae levels associated with the island found several kilometers offshore and tending to be recirculated by current eddies (Colin 2009). This phenomenon, known as "sticky water", has also been documented on the Great Barrier Reef (Wolanski and Spagnol 2000) and in mangrove forests (Furukawa et al. 1997).
Figure 4.9 Locations of the island arcs of Palau and Yap. Reef locations are shown in orange. The North Equatorial Current (NEC) is shown, along with the Mindanao Eddy (ME) and the Palau Eddy (PE), which is present during the summer.
4.2.1.6 *The Maldives Islands*

The Maldives are a chain of 22 coral atolls, which span 800 kilometers north to south in the Indian Ocean just south of the Indian subcontinent and are shown in Figure 4.10. There is minimal topographical relief in the Maldives, as the highest point above sea level is 5m. Of the 1200 coralline islands making up the chain, only around 200 are inhabited (Spalding et al. 2001). The climate and surface flow conditions depend directly on the Asian monsoon. Air temperature varies little during the year, with the dry season occurring during the northeast monsoon (winter) and maximal rainfall during summer (Spalding et al. 2001). A reversal in surface ocean currents also occurs in the region, with the eastward flowing Southwest Monsoon Current (SMC) present in summer and the westward flowing Northeast Monsoon Current (NMC) present in winter (Shenoi et al. 1999).
**Figure 4.10** Reefs of the Maldives Islands. Reefs are in orange and mangroves in green. Surface currents here result from the monsoonal wind pattern, with the North Monsoonal Current (NMC) predominant in the winter and the South Monsoonal Current during the summer (Shenoi et al. 1999).

### 4.2.1.7 Florida Keys

The Florida Keys are a long chain of islands, bordered to the south and east by a continuous reef tract located at the south end of the Florida peninsula as shown in Figure 4.11. The reef tract separates Florida Bay and the Straits of Florida, through which the Florida Current flows before feeding into the Gulf Stream. The reef tract is commonly subdivided into three main regions, the Lower, Middle, and Upper Keys as shown in Figure 4.11. Florida Bay is shallow and receives CDOM-rich water in the form of run-off from the Florida Everglades, which lie north of Florida Bay. Inputs of fresh water from
the Everglades, primarily during the summer wet season, eventually leave Florida Bay through channels in the chain of islands, flow over the reef tract, join the Florida Current, and are transported northeast into the Gulf Stream as shown by blue arrows in Figure 4.11 (Johns et al. 2006).

Figure 4.11 The reefs of the Florida Keys. Reef locations are in orange and mangroves in green. Blue arrows indicate water flow, with water from the Everglades and Florida Bay exiting through channels in the Middle Keys and being pulled northward by the fast-flowing Florida Current. Hawk Channel, which lies between the reef tract (orange) and the chain of islands is shown in red. Mangroves are shown in green.
4.2.1.8 The Islands of the Bahamas

Previously described in Chapter 3, the Bahamas is archipelago made up of many islands surrounding two large, shallow bank regions, known as Great Bahama Bank and Little Bahama Bank. Reefs are found mostly on the eastern margins of the banks and islands as shown in Figure 4.12 (Spalding et al. 2001). The majority of surface flow in the region is due to the North Equatorial Current (NEC) and the Gulf Stream, and their flows are diverted around the shallow banks. Currents in Exuma Sound are generally to the northwest (Colin 1995).

Figure 4.6 Reefs in the Islands of the Bahamas. Reefs are shown in orange and mangroves in green. Blue arrows indicate surface circulation.
4.2.1.9 Panama

Coral reefs in Panama are located in both the western Caribbean Sea and in the eastern Pacific Ocean. On the Caribbean coast of Panama, reefs are located in two primary areas: The Bocas del Toro region and eastward from the city of Cristóbal continuing along the San Blas Archipelago (Spalding et al. 2001). Figure 4.13 shows reefs and mangroves on both the Caribbean and Pacific coasts of Panama. Reefs on the Pacific coast of Panama are found in the Gulf of Panama and the Gulf of Chiriqui. The Pacific coast of Panama, particularly in the Gulf of Panama, experiences large extremes in water temperature, including warm events due to El Nino, where water temperatures can reach 33°C. During cool events associated with annual wind-driven upwelling during the winter dry season in the Gulf of Panama, water temperatures can dip to 15°C (Spalding et al. 2001). Wind-driven upwelling is almost nonexistent in the Gulf of Chiriqui due to mountains in the Central American cordillera which block prevailing northeast winds (D'Croz and O'Dea 2007).
4.2 METHODS

4.2.1 Satellite imagery

The Sea-Viewing Wide Field of View Sensor (SeaWiFS) was launched on 01 August 1997 aboard the SeaStar spacecraft and was operational until 2009. Moderate Resolution Imaging Spectrometer (MODIS) sensors were launched aboard two spacecraft beginning with the ProtoFlight Model (PFM) sensor aboard the Terra (EOS AM-1) spacecraft, launched on 18 December 1999. The Flight Model 1 (FM1) sensor aboard the Aqua (EOS PM-1) spacecraft was launched on 04 May 2002 (MODIS website). Due to several technical issues, MODIS Terra data are unreliable and was not used in this study. To create as long and as accurate a time series as possible, images from SeaWiFS were
used for years 1997-2003 and MODIS Aqua images for years 2003-2009. Data from the two sensors were merged by creating a time series during a period (2003-2005) when data were available from both sensors. Details of the data merging approach are found in Section 4.5.2.1.

For each geographic region of interest (ROI) analyzed in this study (Table 4.1), SeaWiFS (January 1998 - December 2002) and MODIS (January 2003 - December 2010) image files were ordered from NASA's Ocean Biology Processing Group using the Level 1/Level 2 visual browser at oceancolor.gsfc.nasa.gov. Level 2 (L2) files have been corrected for atmospheric effects and contain Rrs bands in the visible and near-infrared regions of the spectrum as well as a set of standard products. Daily local area coverage (LAC) L2 files containing the desired parameters were ordered, which have a nominal spatial resolution of 1 km. Once ordered, hierarchical data format (HDF) files were queued on a NASA server and downloaded to a 2TB external hard drive. All image files were then processed on a MacBook Pro running Mac OS X version 10.6.8. IDL-based SeaDAS (version 6.3) image processing routines were used to map the level 2 images into 700 pixel x 550 pixel or 425 pixel x 335 pixel mapped level 3 (L3) files using an equidistant cylindrical projection in various regions of interest (ROIs).

After files were mapped, several flags were used to mask out pixels with questionable values. The flags used to mask out certain pixels were land, atmospheric correction failure, clouds and ice, high sun glint, high solar zenith angle, high satellite zenith angle, cloud shadow, and high light saturation of the sensor. Pixels where these flags were present were masked out and not used in subsequent processing and time series analyses. Once questionable pixels were masked out, daily images in each ROI
were saved in a native IDL file format before further processing.

Daily image files were then subsetted to desired points of interest (POI) within each ROI in order to reduce disk space and processing time. Within each ROI, points of interest were input using coordinates of latitude and longitude. For each POI, an Interactive Data Language (IDL) routine was used to find the nearest pixel to each set of coordinates. This was designated as the center pixel, and around this center pixel, a 7 pixel by 7 pixel box was calculated. For some regions (Bahamas and Florida Keys) a 3 pixel by 3 pixel box was used to allow for POIs to be placed as close to reefs of interest as possible. In many other regions, however, 15-pixel by 15-pixel boxes were required in order to include as many pixels as possible due to excessive cloud cover during certain times of the year. Percentages of 7-day time bins with valid observations based on region of interest are listed in Table 4.2. Red text indicates time periods and ROIs with percentages of valid observations below 70%, which were not used in further analyses.
Table 4.2  Percentage of 7-day time bins with valid observations based on time period and region of interest.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Baha</td>
<td>3km$^2$</td>
<td>94%</td>
<td>91%</td>
<td>94%</td>
<td>90%</td>
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<tr>
<td>Bali</td>
<td>15km$^2$</td>
<td>41%</td>
<td>77%</td>
<td>61%</td>
<td>87%</td>
</tr>
<tr>
<td>GBRn</td>
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<td>80%</td>
<td>84%</td>
<td>84%</td>
<td>84%</td>
</tr>
<tr>
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<td>84%</td>
<td>91%</td>
<td>89%</td>
<td>92%</td>
</tr>
<tr>
<td>GBRs</td>
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<td>90%</td>
<td>94%</td>
<td>94%</td>
<td>95%</td>
</tr>
<tr>
<td>Keys</td>
<td>3km$^2$</td>
<td>92%</td>
<td>92%</td>
<td>94%</td>
<td>90%</td>
</tr>
<tr>
<td>MalD</td>
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<td>31%</td>
<td>81%</td>
<td>81%</td>
<td>82%</td>
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<tr>
<td>PALA</td>
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<td>72%</td>
<td>76%</td>
<td>66%</td>
<td>81%</td>
</tr>
<tr>
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<td>76%</td>
<td>79%</td>
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<td>84%</td>
<td>87%</td>
<td>82%</td>
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<tr>
<td>PHIC</td>
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<td>81%</td>
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<td>79%</td>
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<tr>
<td>PHIE</td>
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<td>82%</td>
<td>85%</td>
<td>81%</td>
</tr>
<tr>
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<td>86%</td>
<td>87%</td>
<td>86%</td>
</tr>
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<td>77%</td>
<td>80%</td>
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<td>YAP</td>
<td>7km$^2$</td>
<td>63%</td>
<td>67%</td>
<td>57%</td>
<td>73%</td>
</tr>
</tbody>
</table>

In each 49 square pixel box, remote-sensing reflectance values at five relevant visible bands (412nm, 443nm, 490nm, 555nm and 670nm) were extracted and used to calculate other products. Chlorophyll concentration using the default algorithm (O’Reilly et al. 2000) and photosynthetically available radiation (PAR) calculated using the algorithm of Frouin et al. (2003) are standard L2 products for SeaWiFS and MODIS, which are included in L2 files downloaded from NASA. An IDL sub-routine was used to solve the equations of the quasi-analytical algorithm (QAAv5) of Lee et al. (2009) and determine the following quantities: absorption due to CDOM at 443nm [$a_{CDOM}(443)$], absorption due to pigmented particles at 443nm ($a_{ph}(443)$), and the backscattering coefficient at 443nm ($b_{bp}(443)$). Chlorophyll concentration using the algorithm of Carder et al. (1999) was calculated from $a_{ph}(443)$. All of the parameters used in time series
analyses are given in Table 4.3 along with the appropriate references. Details of the QAA and Carder algorithms can be found in Section 2.4. Coefficients used in the implementation of the Lee and Carder algorithms are found in Table 4.4.

Table 4.3 Parameters used in time-series analyses

<table>
<thead>
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<th>Parameter</th>
<th>Algorithm name</th>
<th>Reference</th>
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<td>a&lt;sub&gt;CDOM&lt;/sub&gt; at 443nm</td>
<td>Quasi-analytical (QAA)</td>
<td>Lee et al. (2009)</td>
</tr>
<tr>
<td>a&lt;sub&gt;ph&lt;/sub&gt; at 443nm</td>
<td>Quasi-analytical (QAA)</td>
<td>Lee et al. (2009)</td>
</tr>
<tr>
<td>b&lt;sub&gt;bp&lt;/sub&gt; at 443nm</td>
<td>Quasi-analytical (QAA)</td>
<td>Lee et al. (2009)</td>
</tr>
<tr>
<td>[Chl]&lt;sub&gt;Card&lt;/sub&gt;</td>
<td>Carder semi-analytical</td>
<td>Carder et al. (1999)</td>
</tr>
<tr>
<td>*PAR</td>
<td>SeaWiFS PAR</td>
<td>Frouin et al. (2003)</td>
</tr>
<tr>
<td>SST</td>
<td>Pathfinder version 5.2</td>
<td>Casey et al. (2011)</td>
</tr>
</tbody>
</table>

* Denotes a standard Level 2 product for SeaWiFS and MODIS.

Table 4.4 Coefficients used in remote sensing algorithms (Equations 2.5, 2.7, 2.19, 2.20)

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<thead>
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<th>Value</th>
<th>Source</th>
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<tbody>
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<td>0.0895</td>
<td>Gordon et al. (1988), Lee et al. (2009)</td>
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<tr>
<td>g&lt;sub&gt;1&lt;/sub&gt;</td>
<td>0.1247</td>
<td>Gordon et al. (1988), Lee et al. (2009)</td>
</tr>
<tr>
<td>a&lt;sub&gt;0&lt;/sub&gt;(443)*</td>
<td>3.59</td>
<td>Carder et al. (1999)</td>
</tr>
<tr>
<td>a&lt;sub&gt;1&lt;/sub&gt;(443)*</td>
<td>0.80</td>
<td>Carder et al. (1999)</td>
</tr>
<tr>
<td>a&lt;sub&gt;2&lt;/sub&gt;(443)*</td>
<td>-0.5</td>
<td>Carder et al. (1999)</td>
</tr>
<tr>
<td>a&lt;sub&gt;3&lt;/sub&gt;(443)*</td>
<td>0.0112</td>
<td>Carder et al. (1999)</td>
</tr>
<tr>
<td>P&lt;sub&gt;0&lt;/sub&gt;*</td>
<td>51.9</td>
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</tr>
<tr>
<td>P&lt;sub&gt;1&lt;/sub&gt;*</td>
<td>1.0</td>
<td>Carder et al. (1999)</td>
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</table>

* Denotes coefficients appropriate for regions with unpackaged pigments.

For sea-surface temperature (SST) data, the Advanced High Resolution Radiometer (AVHRR) Pathfinder Version 5.2 data set was used, which spans the time period from 1981 until 2010 (Casey et al. 2011). These data were provided by GHRSSST and the US National Oceanographic Data Center. This project was supported in part by a grant from the NOAA Climate Data Record (CDR) Program for satellites. Global daily SST files at 4km resolution (8640 pixels x 4320 pixels) were downloaded from.
http://data.nodc.noaa.gov/pathfinder/Version5.2/ in NetCDF file format. Each pixel of each image has an associated quality level from zero to 5. A quality level of zero represents clouds and land, while a quality level of 1 represents pixels too close to land to be useful. Quality level 2 represents the lowest quality value for useful data. For this study, only data with a quality level of 3 or higher were used. All pixels with a quality level of less than 3 were masked out and eliminated from further analyses. Because SST data in this study have a spatial resolution of 4km, a box of 3 pixels by 3 pixels (144 km²) was created instead of the 7 by 7 pixel box was used for ocean color data.

An IDL routine was used to bin daily arrays of $a_{CDOM}(412)$, $a_{ph}(443)$, $b_{bp}(443)$, [Chl]$_{Card}$, PAR, and SST into a series of 7-day time bins by POI, keeping the data at 1km-resolution (4km for SST). For each parameter at each POI, the mean, variance, and number of observations in each time bin were computed. The end result was a series of 684 time bins for the years 1997-2010, with 52 time bins per year for 13 years. For each POI, a file containing the number of observations, mean, and variance for each parameter was compiled and input into Matlab (version 7.4) for plotting and statistical analysis.

4.2.2 Numerical analyses

4.2.2.1 Transition between SeaWiFS and MODIS sensors

Because the time series used in this study was constructed using two different ocean color sensors; the SeaWiFS sensor (1997-2003) and the MODIS sensor (2003-2010), a method was required to merge data from the two sensors. For some parameters, a slight "break" was observed at the end of 2002, where SeaWiFS data transitions to MODIS data. To eliminate this break and ensure a smooth transition from one sensor to the other, a three-year "overlap" time series (2003-2005) using data from both sensors
was created. In each binned time period and for each parameter, a difference between the SeaWiFS value and the MODIS value was calculated. Then, the median value of the differences over the entire "overlap" time series was determined and used as a bias to raise or lower the SeaWiFS time series to match the MODIS time series. The MODIS sensor being a more modern sensor, its values were taken as "true" and SeaWiFS values were matched to it. Bias values used to adjust SeaWiFS data ranged from 1-2% for some parameters and negligible for others.

4.2.2.2 Removal of outlying values

Once data were imported into Matlab and the transition between ocean color sensors addressed, a seasonal cycle often referred to as a climatology of each parameter was calculated by determining the median of each time bin for all years in the time series. For example, the weekly seasonal cycle for time bin 1 (01 January - 07 January) is the median value of all years for time bin 1. The seasonal cycle for each parameter has 52 values, one for each week of the year. The purpose of calculating a median-based seasonal cycle is to identify outlying values in each time series by comparing them to the mean annual cycle (MAC). Calculating a seasonal cycle using median values reduces the effect of extreme outliers on the seasonal cycle. Residual values were calculated by subtracting each value in the time series from the calculated seasonal cycle. Then, for each parameter, a histogram of the absolute value of the residual values was plotted and outlier values were determined by visually inspecting the histogram and selecting a value, termed the critical value. Once critical values for each parameter were determined by visual inspection, values in the original time series that deviated positively or negatively from the seasonal cycle by more than the critical value were removed. Missing or flagged
values and outliers were turned into NaN (not a number) values in Matlab, which are treated as missing values and interpolated during subsequent analyses.

4.2.2.3 Interpolation of missing values

Once outlying values are removed, the interpolation of missing values is required to replace values rejected as outliers as well as data points rejected due to poor data quality or the presence of a flag such as land, cloud or ice, high solar zenith angle, etc. Rather than a simple linear interpolation approach, which gives equal treatment to all values regardless of uncertainty, a weighted interpolation scheme was used where values with lower uncertainty are weighted more strongly than those with higher uncertainty. Because the interpolation of missing data points relies on the uncertainty associated with each data point, the missing variances were replaced first using Equation 4.1.

\[
\sigma^2_{\bar{x}} = \frac{\sigma_1 \cdot \sigma_2}{\sqrt{(\sigma_1^2 + \sigma_2^2)}}
\] (4.1)

To find the missing variances \(\sigma_{\bar{x}}\), the two nearest symmetrically adjacent points are used as \(\sigma_1\) and \(\sigma_2\) respectively. Once the missing variances are replaced, the missing data values \(\bar{x}\) can be determined using the following by using the two nearest symmetrically adjacent points as \(x_1\) and \(x_2\):

\[
\bar{x} = \frac{\sigma_2 x_1 + \sigma_1 x_2}{\sigma_1^2 + \sigma_2^2}
\] (4.2)
The use of weighted interpolation reduces the influence of data points with high uncertainties.

4.2.2.4 Further calculations and propagation of uncertainty

Once the time series of each parameter was interpolated to remove missing values, a second mean annual cycle was calculated, this time using the mean values of each weekly time bin. A second set of residuals was also then calculated, which can be thought of as "anomalies", where the time series deviates from the mean annual cycle. For each parameter of interest, a plot of the time series, mean annual cycle, and residuals were generated for each point of interest and inspected visually. A set of characteristic values of each location was also exported to a separate file to allow comparisons between locations. These values included the mean and standard deviation of $a_{CDOM}(412)$, $a_{ph}(443)$, $[Chl]_{Card}$, and SST. The minimum, maximum, and range of the mean annual cycle were also computed. Certain time periods were examined more closely, including periods of coral bleaching, such as the period from October to May on the Great Barrier Reef (Berkelmans 2004).

To estimate the uncertainty of values calculated (i.e., means, ratios, seasonal cycles, etc.) from time series data, a Monte Carlo approach was utilized based on the variances of the values used in the calculations. To determine uncertainty, two calculations were done; one with the original numbers and one with a simulated data set, or a set of realizations. The set of realizations of a particular variable was created by generating a set of normally distributed random numbers with a mean of zero for each point in the time series. This set of random numbers is multiplied by the variance of each number in the original calculation and then added to that same number in the original calculation to
create a set of realizations. For example, when doing a calculation using two numbers, each number involved in the calculation would have a set of realizations associated with it that would be put through the same calculations as the original two numbers. After the calculation is complete, a histogram of the set of realization calculations was examined. If the set of realizations is sufficiently large, the mean of the set of realizations will approach the output of the original calculation and the standard deviation of the set of realizations represents the uncertainty of that calculation. Tests were done with different numbers of realizations to find the number needed for the mean of the set of realizations to converge on the value of the original calculation. After several trials, 300 realizations of each number involved in a calculation were found to be sufficient to achieve the desired results without incurring extra processing time.

4.2.2.5 Significance of seasonal cycles

One way to compare temporal variability in different locations is to examine the seasonal cycle. To assess whether the measured seasonal cycles were significant, or if variations were within the noise level, a simple test was done to compare uncertainties in the measured seasonal cycles. Once seasonal cycles for each week of the year were calculated, two important numbers were determined, the minimum and maximum value of the seasonal cycle. These two numbers will be referred to as the minimum and maximum of the mean annual cycle (MAC), notated as $\text{MAC}_{\text{min}}$ and $\text{MAC}_{\text{max}}$. A third number can be calculated by subtracting $\text{MAC}_{\text{min}}$ from $\text{MAC}_{\text{max}}$, which is the range of the mean annual cycle, notated as $(\text{MAC}_{\text{rng}})$. Equation 4.3 is used to determine whether a calculated seasonal cycle is significant ($\text{MAC}_{\text{sig}}$).
\[
MAC_{sig} = \frac{MAC_{rng}}{\sqrt{\sigma^2_{min} + \sigma^2_{max}}} 
\] (4.3)

4.2.3 Selection of points of interest (POI) for time-series analysis

Individual points of interest where time series of satellite data were extracted were chosen for their proximity to coral reefs, many of which experienced coral bleaching during the time period from 1998-2010. Points of interest were selected to include as many possible different reef environments within a region. The Great Barrier Reef, for example, is a very large region with many different reef environments, so more POIs were selected there than in Palau, which covers a much smaller area with a smaller number of reef environments.

Because ocean-color satellite data is influenced by the reflection of light by the seafloor in shallow waters, points of interest were chosen in areas where water depths are greater than 30m to prevent bottom reflection from contaminating estimates of water column optical properties. Points of interest were chosen by visual inspection of aerial imagery and bathymetric data using Google Earth version 6.1.0, which contains bathymetric data from a variety of sources including Scripps Institute of Oceanography (SIO), the United States Navy (USN), the National Oceanic and Atmospheric Administration (NOAA), the National Geospatial-Intelligence Agency (NGA), and the General Bathymetric Chart of the Oceans (GEBCO). Points were chosen to be as close as possible to coral reef locations without having any extracted data from waters shallower than 30m. To allow comparison of the optical properties of coasts with
mangroves and those without mangroves, some study locations were chosen adjacent to coastal areas with mangroves and also adjacent to coasts lacking mangroves.

### 4.2.4 Coral reef and mangrove distribution data

#### 4.2.4.1 Global distribution of coral reefs

The distribution for coral reefs used to create maps were obtained from the Millennium Coral Reef Mapping Project provided by the Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF) and Institut de Recherché pour le Développement (IRD, Centre de Nouméa), with support from NASA. These data were downloaded as an ArcGIS shape file and plotted using the ArcMAP version 10.1 software suite.

#### 4.2.4.2 Global distribution of mangroves

The dataset containing the distribution of mangroves shown in maps was obtained from the United Nations Environmental Programme World Conservation Monitoring Center (UNEP-WCMC). This recent dataset quantifies the global distribution of mangroves using a detailed classification analysis of over 1000 images from the Landsat satellite. Details of the dataset and how it was assembled can be found in Giri et al. (2011). These data were downloaded as an ArcGIS shape file and plotted using the ArcMAP version 10.1 software suite.

### 4.2.5 Meteorological data

Monthly averages (in millimeters) of rainfall data for the Great Barrier Reef were obtained from the Australian Bureau of Meteorology website at
http://www.bom.gov.au/climate/averages/tables/ca_qld_names.shtml. Rainfall data were obtained for the following cities which lie along the GBR, listed from north to south: Lockhart, Cooktown, Cairns, Innisfail, Townsville, Mackay, and Rockhampton. Locations where meteorological data was obtained are shown in Figure 4.14.

Monthly wind direction distribution data at locations in several ROIs were generated using local weather station observations from October 2009 until present and accessed at http://www.windfinder.com/windreports/windkarte_world.htm.

4.2.6 Hydrolight simulations

Hydrolight is a software program used to calculate apparent optical properties (AOPs) of the water column from a set of inherent optical property (IOP) inputs based on the radiative transfer model described in Mobley (1994). Details of the model and its implementation can be found in Mobley and Sundman (2012). Similar to Hydrolight simulations carried out in Chapter 3, the Case II model for IOP input was used in Hydrolight version 5.1 with inputs defined in Table 4.5. Boundary conditions, such as sky radiance, bottom effects, and wind speed were held constant over all runs and can be found in Table 3.2. Twenty-four simulations were run, with "high" and "low" absorption regimes for each of twelve regions as defined in Table 4.5. Values of chlorophyll concentration for input into Hydrolight were calculated from a_p(chl)(443) values using the relationship of Carder et al. (1999), which is described in Section 2.6. Outputs from Hydrolight modeling were spectral downwelling irradiance spectra from which UV/PAR ratios were calculated by integrating the area under the irradiance spectra in the UV (300nm - 400nm) divided by the area under the irradiance spectra in the visible region.
(400nm - 700nm). The shortest wavelength of light that can be modeled using Hydrolight is 300nm. A value for percent of surface irradiance in the UV was also calculated by comparing the integrated areas under the irradiance spectra in the UV at the surface compared to a depth of 5m.

4.3 RESULTS

4.3.1 Time-series results grouped by reef area

Results are presented first by region, followed by a comparison of data from all regions. At all locations in each region, mean values of $a_{CDOM}(443)$ and $a_{ph}(443)$ over the entire time series are plotted along with the range of the seasonal cycle and the uncertainty in the seasonal cycle range. Plots of the full 13-year time series are shown in order to compare time series at two or more locations of particular interest.

4.3.1.1 Great Barrier Reef

Results from the GBR are split into the southern, central, and northern sections, as defined in Table 4.1. Locations in the southern GBR where satellite time series data were extracted are shown in Figure 4.14 along with locations where meteorological data were obtained at Mackay and Rockhampton. Within the southern GBR, time series data were extracted at 38 locations. These were subdivided into two groups, locations in the outer reef matrix and locations in the lagoon. For $a_{CDOM}(443)$, five pieces of information at each location are shown in Figure 4.15: The mean $a_{CDOM}(443)$ value for the entire time series (blue squares); the upper and lower extent of the seasonal cycle (red bars); and
uncertainty associated with the upper and lower extent of the seasonal cycle (black bars).

The same information for $\alpha_{ph}(443)$ is shown in Figure 4.16.

Figure 4.8 Locations of extracted time series data in the southern GBR. Reefs are shown in orange and mangroves in green. Marker colors represent the mean value of $a_{CDOM}(443)$ over the entire time series. Locations where time series data are plotted (Figs. 4.15 - 4.22) are named and denoted by yellow circles.
Figure 4.9 Values of $a_{CDOM}$ at 443nm for all locations in the southern Great Barrier Reef ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values. Locations plotted in Figs. 4.18-4.26 are named.

Figure 4.10 Values of $a_{ph}$ at 443nm for all locations in the southern Great Barrier Reef ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.
Locations HRN05 and KEP01 are located 135km apart at the southern end of the GBR. Both KEP01 and HRN05 are approximately 45km from shore and selected as close to shore as possible, given the influence of seafloor reflectance in waters less than 30m deep. Figures 4.17 and 4.18 show rainfall data from Rockhampton plotted with time series of \( a_{\text{CDOM}}(443) \) values from KEP01 (Fig. 4.17) and HNR05 (Fig. 4.18). Note the periodic absorption spikes at KEP01 to around 0.1m\(^{-1}\) aligned with rainfall events that are not present at HRN05. Values of \( a_{\text{CDOM}}(443) \) and \( a_{\text{ph}}(443) \) at locations KEP01 and HRN05 are plotted in Figure 4.19. In Figure 4.19, and in all subsequent full time-series plots, time series data is plotted in blue with the seasonal cycle in red.

Locations SW08 and SW06 (Figure 4.14) are located 90km apart in the outer reef matrix, with SW08 on the lagoon side of the matrix and SW06 at the outer edge of the matrix adjacent to the Coral Sea. The annual cycle at SW08 has a much higher range with higher anomalies than at SW06, a more offshore location at the edge of the Coral Sea. Note the difference in y-axis scaling between Figures 4.19 and 4.20, with the two outer matrix locations (SW08 and SW06) showing lower overall levels of absorption due to both CDOM and phytoplankton compared to the two lagoon locations (KEP01 and HRN05). A SeaWiFS image showing levels of \( a_{\text{CDOM}}(443) \) on the southern GBR from 22 May 1998 is shown in Figure 4.21. Note how location HRN05 is located in an area with low \( a_{\text{CDOM}}(443) \) levels although it is close to shore. Nearshore flow in the northward direction is impeded by Fraser Island, creating a pocket of low \( a_{\text{CDOM}}(443) \) in the vicinity of the HRN05 location.
Figure 4.17 Monthly rainfall data (red, right y-axis) from Rockhampton and $a_{\text{CDOM}}(443)$ (blue, left y-axis) at the KEP01 location. KEP01 is located 45km east of the mouth of the Fitzroy River, which enters the GBR at Rockhampton.

Figure 4.18 Monthly rainfall data (red, right y-axis) from Rockhampton and $a_{\text{CDOM}}(443)$ (blue, left y-axis) at the HRN05 location. HRN05 is located 150km southeast of the mouth of the Fitzroy River, which enters the GBR at Rockhampton.
Figure 4.11 Time series of $a_{CDOM}(443)$ and $a_{ph}(443)$ at locations KEP01 and HRN05 in the southern GBR. Values of $a_{CDOM}(443)$ and $a_{ph}(443)$ for KEP01 are shown in plots A and B respectively and values for HRN05 are in plots C and D. Grayed areas indicate the summer rainy season in Australia.

Figure 4.12 Time series plots of $a_{CDOM}(443)$ and $a_{ph}(443)$ at locations SW08 and SW06 on the southern GBR. Values of $a_{CDOM}(443)$ and $a_{ph}(443)$ for SW08 are shown in plots A and B respectively and values for SW06 are in plots C and D. Grayed areas indicate the summer rainy season in Australia.
Figure 4.21 SeaWiFS image of $a_{\text{CDOM}}(443)$ from 22 May 1998 on the southern Great Barrier Reef. Locations KEP01, HRN05, SW08, and SW06 are denoted by yellow circles.

In the central GBR, time series data were extracted at 63 locations shown in Figure 4.22 along with rainfall data at Cooktown, Cairns, Innisfail, and Townsville. As with the southern GBR, locations were subdivided into two groups, locations in the outer reef matrix and locations in the lagoon. Values of $a_{\text{CDOM}}(443)$ for each location in the central GBR are plotted in Figure 4.23, showing the mean $a_{\text{CDOM}}(443)$ value for the entire time series (blue squares), the upper and lower extent of the seasonal cycle (red bars), and the uncertainty associated with the upper and lower extent of the seasonal cycle (black bars). The same information for $a_{\text{ph}}(443)$ is shown in Figure 4.24. Locations in the lagoon have higher uncertainties associated with the minima and maxima of the seasonal cycles, as seen by the black bars in Figures 4.23 and 4.24. Locations in the outer matrix tend to
have overall lower values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ with much less variation in the seasonal cycle. Figures 4.25 and 4.26 show rainfall data from Townsville plotted with time series of $a_{\text{CDOM}}(443)$ values from CEN02 (Fig. 4.25) and an outer matrix location, CEN65 (Fig. 4.26). Note the periodic absorption spikes aligned with rainfall events at CEN02, compared to the lack of correlation between rainfall and $a_{\text{CDOM}}(443)$ at the CEN65 location. A SeaWiFS image from 28 March 1998 is shown in Figure 4.27 of $a_{\text{CDOM}}(443)$ on the Central GBR. Note Coral Sea water impinging on the continental shelf where the density of reefs in the matrix is low.

Figure 4.22 Locations of extracted time series data in the central GBR. Reefs are shown in orange and mangroves in green. Marker colors represent the mean value of $a_{\text{CDOM}}(443)$ over the entire time series. Locations where time series data are plotted (Figs. 4.33 - 4.37) are named and denoted by yellow circles.
Figure 4.23 Values of $a_{\text{CDOM}}(443)$ for all locations in the central Great Barrier Reef ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values. Locations plotted in Figs. 4.18-4.26 are named.

Figure 4.24 Values of $a_{\text{ph}}(443)$ for all locations in the central Great Barrier Reef ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.
Figure 4.25 Rainfall and absorption due to CDOM at the CEN02 location. Monthly rainfall data (red, right y-axis) from Cairns and $a_{\text{CDOM}}(443)$ (blue, left y-axis) at the CEN02 location. CEN02 is located 40km east of the mouth of the Ross River, which enters the GBR at Townsville.

Figure 4.26 Rainfall and absorption due to CDOM at the CEN65 location. Monthly rainfall data (red, right y-axis) from Cairns and $a_{\text{CDOM}}(443)$ (blue, left y-axis) at the CEN65 location. CEN65 is located 100km northeast of the mouth of the Ross River, which enters the GBR at Townsville.
In the northern section of the GBR, time series data were extracted at 21 locations shown in Figure 4.28. Because the lagoon narrows considerably in the northern GBR, a distinction between locations in the outer matrix and those in the lagoon is not useful. Values of $a_{CDOM}(443)$ and $a_{ph}(443)$ for each location in the northern GBR are plotted in Figures 4.29 and 4.30 respectively, along with the extent of the seasonal cycle and the associated uncertainties. Full time series at locations NOR05 and NOR05a are plotted in Figure 4.31. While the NOR05 location is within the reef matrix and NOR05a lies just outside the matrix only 20km to the northeast, time series at the two locations are quite different. The time series at NOR05 has overall higher levels of $a_{CDOM}(443)$ and $a_{ph}(443)$.
as well as a higher range in the seasonal cycle, which can be seen in Figures 4.29, 4.30, and 4.31.

**Figure 4.28** Locations of extracted time series data in the northern GBR. Reefs are shown in orange and mangroves in green. Marker colors represent the mean value of $a_{\text{CDOM}}(443)$ over the entire time series. Locations where time series data are plotted (Fig. 4.31) are named and denoted by yellow circles.
Figure 4.29 Values of $a_{CDOM}(443)$ for all locations in the northern Great Barrier Reef ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle (MACrng), and black bars represent the uncertainty of the MACrng values.

Figure 4.30 Values of $a_{ph}(443)$ for all locations in the northern Great Barrier Reef ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle (MACrng), and black bars represent the uncertainty of the MACrng values.
4.3.1.2 Thailand

Locations in Thailand where time-series data at 19 locations were extracted are shown in Figure 4.32. These locations span two ROIs, the central and northern portions of the Thai peninsula, which include locations in both the Andaman Sea and Gulf of Thailand. Time-series data from the southern part of the Thai peninsula were not analyzed due to high cloud cover and a very low (56%) percentage of valid observations (Table 4.2). Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for each location in the Andaman Sea and Gulf of Thailand are plotted in Figures 4.33 and 4.34 respectively, along with the extent of the seasonal cycle and the associated uncertainties. A comparison of locations in the Andaman Sea and Gulf of Thailand is shown in Figure 4.35 with plots of full time series.
Climate on the Thai peninsula is largely determined by the Asian monsoon with northeast winds during the winter and southeast winds during the summer. Time series from locations on both sides of the Thai peninsula show increased levels of $a_{\text{CDOM}}(433)$ and $a_{\text{ph}}(443)$ during the winter months (white areas in Figure 4.35), which does not coincide with the rainy season in Thailand (May-October). This is in contrast to the GBR, where maximal values of the seasonal cycles of $a_{\text{CDOM}}(433)$ and $a_{\text{ph}}(443)$ occur during the rainy season. One possible reason for this is that strong winds are driving coastal upwelling in the area from November until March, bringing nutrient-rich waters to the surface. Increased levels of CDOM and chlorophyll would be expected to result from such a phenomenon (Coble et al. 1998, Coble 2007). If this is the case, it would be expected that in areas shielded from the winds, this wintertime pattern of high absorption values during the winter would not be observed. Figures 4.36 and 4.37 show full time series at four locations (MER03, MER04, AND02, and PUK03), shown in order from north to south.
Figure 4.14 Locations with extracted time series data in Thailand. Colors represent $a_{cdom}(443)$ (m$^{-1}$). Locations with plotted data are circled in yellow. Reefs are in orange and mangroves in green. Mountain range with elevations reaching 700m on the Thai peninsula is indicated by the black oval.
Figure 4.15 Values of $a_{CDOM}(443)$ for all locations in the Thailand ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle (MAC$_{mg}$), and black bars represent the uncertainty of the MAC$_{mg}$ values.

Figure 4.34 Values of $a_{ph}(443)$ for all locations in the Thailand ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle (MAC$_{mg}$), and black bars represent the uncertainty of the MAC$_{mg}$ values.
Figure 4.35 Time series plots of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ at locations PUK01 and GTA02 in Thailand. Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for PUK01 are shown in plots A and B respectively and values for GTA02 are in plots C and D. Grayed areas indicate the rainy season in central Thailand (May-Nov), which coincide with the SW monsoon.

As seen in Figures 4.36 and 4.37, locations MER04 and AND02 exhibit much smaller increases in the levels of $a_{\text{CDOM}}(433)$ and $a_{\text{ph}}(443)$ during the winter months, compared to locations to both the north (MER03) and south (PUK03). The two middle locations lacking increased absorption levels during the winter are in fact sheltered from the winds due to a range of mountains on the central Thai peninsula shown in Figure 4.32. It is hypothesized that variability in $a_{\text{CDOM}}(433)$ and $a_{\text{ph}}(443)$ is reduced in this area due to lack of wind-driven upwelling. A meteorological station in the sheltered area shows westerly winds in the area during the winter, compared to strong easterly and northeasterly winds elsewhere along the Thai peninsula.
Figure 4.36 Time series of $a_{\text{CDOM}}(443)$ values at locations MER03 (A), MER04 (B), AND02 (C), and PUK03 (D), located along the Andaman coast in Thailand (Fig 4.32). Note the low $a_{\text{CDOM}}(443)$ peaks at the two middle locations (MER04 and AND02) during the NE monsoon from May until October (white areas). Grayed areas represent the SW monsoon.

Figure 4.37 Time series of $a_{\text{ph}}(443)$ values at locations MER03 (A), MER04 (B), AND02 (C), and PUK03 (D), located along the Andaman coast in Thailand (Fig 4.32). Note the lack of $a_{\text{ph}}(443)$ peaks at the two middle locations (MER04 and AND02) during the NE monsoon from May until October (white areas). Grayed areas represent the SW monsoon.
This pattern is also visible in plots of time series of sea-surface temperature shown in Figure 4.38, where low-temperature spikes are more prominent during the winter months at locations MER03 and PUK03, which are locations more exposed to wind-induced upwelling, compared to locations MER04 and AND02. The range of SST values at locations MER03 and PUK03 is approximately 8°C, compared with an approximate range of 6°C at locations MER04 and AND02, which are sheltered from the wind and experience less upwelling during the winter months.

Figure 4.38 Time series of SST values at locations MER03 (A), MER04 (B), AND02 (C), and PUK03 (D), located along the Andaman coast in Thailand (Fig 4.32). Grayed areas represent the SW monsoon.
4.3.1.3 Bali

Extracted data from nine locations in Bali are shown in Figure 4.39 with colored circles representing $a_{\text{CDOM}}(443)$ values. Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for each location near Bali are plotted in Figures 4.40 and 4.41 respectively, along with the extent of the seasonal cycle and the associated uncertainties. The lowest mean $a_{\text{CDOM}}(443)$ values were found at location LOM04, which is in the middle of the Lombok Strait, one of three main outlet points for water from the Pacific Ocean which flows through the islands of the Philippines as part of the Indian Throughflow described in Section 4.2.1.3 and shown in Figure 4.7.

**Figure 4.39** Locations with extracted time series data near Bali. Colors represent mean values of $a_{\text{CDOM}}(443)$ over the entire time series. Locations with plotted data are circled in yellow. Reefs are in orange and mangroves in green.
Figure 4.40 Values of $a_{\text{CDOM}}(443)$ for all locations in the Bali ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{mg}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{mg}}$ values.

Figure 4.41 Values of $a_{\text{ph}}(443)$ for all locations in the Bali ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{mg}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{mg}}$ values.
4.3.1.4 The Philippines

Time-series data were extracted at 75 locations in the Philippines as shown in Figure 4.42. Values of $a_{CDOM}(443)$ and $a_{ph}(443)$ for all locations in the Philippines are plotted in Figures 4.43 and 4.44 respectively, along with the extent of the seasonal cycle and the associated uncertainties. As shown in Figure 4.42, elevated levels of mean $a_{CDOM}(443)$ values are observed near interior islands, away from more oceanic water found along the margins of the islands of the Philippines.

![Map of the Philippines showing locations with extracted time series data](image)

**Figure 4.42** Locations with extracted time series data in the Philippines. Colors represent mean values of $a_{CDOM}(443)$ over the entire time series. Locations with plotted data are circled in yellow. Reefs are in orange and mangroves in green.
Figure 4.43 Values of $a_{\text{CDOM}}(443)$ for all locations in the Philippines ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.

Figure 4.44 Values of $a_{\text{ph}}(443)$ for all locations in the Philippines ROI. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.
Full time series at locations SUR01 and BOH01 are plotted in Figure 4.45. The SUR01 location is located closer to the Pacific Ocean and has lower overall levels of and a lower seasonal cycle range of $a_{\text{CDOM}}(443)$ than BOH01, which is located within the interior islands of the Philippines. A contrast between these two locations can also be observed in the satellite image in Figure 4.46. The MODIS image of $a_{\text{CDOM}}(443)$ from 5 March 2005 shows the inflow of Pacific Ocean water into the islands of the Philippines as part of the Indian Throughflow circulation pattern. The image also shows increased levels of $a_{\text{CDOM}}(443)$ among the interior islands, compared to Pacific Ocean water to the east.

Figure 4.45 Time series of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ at locations SUR01 and BOH01 in the Philippines. Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for SUR01 are shown in plots A and B respectively and values for BOH01 are in plots C and D. Grayed areas indicate the SW monsoon (May-October) and white areas represent the NE monsoon (November-April).
Figure 4.46 MODIS image of $a_{\text{CDOM}}(443)$ from 5 March 2005 in the eastern Philippines. Locations SUR01 and BOH01 are denoted by yellow circles.

4.3.1.5 Palau and Yap

The waters around the islands of Palau and Yap are the clearest encountered in this study, with the lowest seasonal cycle ranges of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$. Figure 4.47 shows locations with extracted time-series data. Figures 4.48 and 4.49 show time series mean values and seasonal cycle ranges of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for all locations near the two islands. Note the y-axis scale compared to the Philippines plots (Figures 4.43 and 4.44).
Figure 4.47 Locations where time series data were extracted near Palau and Yap. Symbol colors indicate the mean $a_{CDOM(443)}$ value over the entire time series. Reefs are in orange. Note the difference in scale between the two maps.
Figure 4.48 Values of $a_{\text{CDOM}}(443)$ for all locations near Palau and Yap. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.

Figure 4.49 Values of $a_{\text{ph}}(443)$ for all locations near Palau and Yap. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.
4.3.1.6 The Maldives

In the Maldives, time-series data were extracted at 10 locations as shown in Figure 4.50. Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for all locations in the Maldives are plotted in Figures 4.51 and 4.52 respectively, along with the extent of the seasonal cycle and the associated uncertainties. Locations MAL05 and MAL06 are on opposite sides of the Maldive Archipelago, full time series of which are plotted in Figure 4.55. The highest mean value of $a_{\text{CDOM}}(443)$ was at location MAL08, which lies in the channel between the two rows of islands, surrounded by reefs. Increased absorption values are expected here as this location is exposed to the transport of light-absorbing material from islands to its east and west.

![Figure 4.50](image)

**Figure 4.50** Locations where time series data were extracted in the Maldives. Symbol colors indicate the mean $a_{\text{CDOM}}(443)$ value over the entire time series. Reefs are in orange and locations with plotted data are circled in yellow.
Locations MAL05 and MAL06 lie on the outside margins of the archipelago, where they are exposed to currents from the Indian Ocean during the summer (MAL05) or winter (MAL06). This can be seen in two satellite images (Figures 4.53 and 4.54), where both the summer (eastward) and winter monsoon (westward) currents are visible. This seasonal pattern is also visible in plots of the full time series at locations MAL05 and MAL06 (Figure 4.55), with spikes of increased absorption in the winter at MAL05 due to the transport of material from the island directly to the east. Such wintertime spikes in absorption are not visible at location MAL06, when that location is exposed to clearer water from the Indian Ocean.
Figure 4.51 Values of $a_{\text{CDOM}}(443)$ for all locations in the Maldives. Blue squares represent the time series mean at each location, red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.

Figure 4.52 Values of $a_{\text{ph}}(443)$ for all locations in the Maldives. Blue squares represent the time series mean at each location, red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{rng}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{rng}}$ values.
Figure 4.53 MODIS image of $a_{\text{CDOM}}(443)$ from 15 October 2003 in the Maldives. Locations MAL05 and MAL06 are denoted by yellow circles.

Figure 4.54 MODIS image of $a_{\text{CDOM}}(443)$ from 8 February 2009 in the Maldives. Locations MAL05 and MAL06 are denoted by yellow circles.
4.3.1.7 The Florida Keys

Fourteen locations with extracted time series from the Florida Keys are shown in Figure 4.56. All but one of these locations lies along the seaward side of the reef tract as close as possible to the reefs, given shallow water depths directly over the reef tract. Values of $a_{CDOM}(443)$ and $a_{ph}(443)$ for each location in the Florida Keys are plotted in Figures 4.57 and 4.58. Full time series plots at locations DTORT1 (Dry Tortugas) and SOMBR (Sombrero Key) are shown in Figure 4.59. Time series at both the DTORT1 and SOMBR locations show periodic pulses of highly colored waters from coastal runoff into Florida Bay. One particular peak in October 2003 was due to a dark-water event which originated in Charlotte Harbor (Hu et al. 2004).
Figure 4.56 Locations with extracted time series data in the Florida Keys. Colors represent mean values of $a_{\text{CDOM}}(443)$ over the entire time series. Locations with plotted data are circled in yellow. Reefs are in orange and mangroves in green.

Figure 4.57 Values of $a_{\text{CDOM}}(443)$ for all locations in the Florida Keys. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($\text{MAC}_{\text{mg}}$), and black bars represent the uncertainty of the $\text{MAC}_{\text{mg}}$ values.
Figure 4.58 Values of $a_{ph}(443)$ for all locations in the Florida Keys. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($MAC_{ng}$), and black bars represent the uncertainty of the $MAC_{ng}$ values.

Figure 4.59 Time series of $a_{CDOM}(443)$ and $a_{ph}(443)$ near the Dry Tortugas (DTORT1) and Sombrero Reef (SOMBR) in the Florida Keys. Values of $a_{CDOM}(443)$ and $a_{ph}(443)$ for DTORT1 are shown in plots A and B respectively and values for SOMBR are in plots C and D. Grayed areas indicate winter months. Black oval in plot A represents the dark water pulse of highly colored water in October 2003 due to a dark water event described in Hu et al. (2004).
4.3.1.8 The Bahamas

Time-series data were extracted at 40 locations in the Bahamas, which are shown in Figure 4.60. Mean values of aCDOM(443) and aph(443) are shown in Figures 4.61 and 4.62 respectively, along with the extent of the seasonal cycle and uncertainties at each location. The first five locations from the left in Figures 4.61 and 4.62 (LS15, LS16, LS17, LS19, LS21), are located progressively offshore on a transect line indicated in red in Figure 4.62. Note how absorption values step down incrementally as the locations move away from the Grand Bahama Bank offshore of Lee Stocking Island in the Exuma Chain. This is the same transect line shown used in the CoBOP experiment, which is shown in Figure 3.1B.

Figure 4.60 Locations with extracted time series data in the Bahamas. Colors represent mean values of aCDOM(443) over the entire time series. Locations with plotted data are circled in yellow. Reefs are in orange and mangroves in green. Red line indicates transect line along which locations LS15, LS16, LS17, LS19, and LS21 lie.
Figure 4.61 Values of $a_{CDOM}(443)$ for all locations in the Bahamas. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($MAC_{mg}$), and black bars represent the uncertainty of the $MAC_{mg}$ values.

Figure 4.62 Values of $a_{ph}(443)$ for all locations in the Bahamas. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle ($MAC_{mg}$), and black bars represent the uncertainty of the $MAC_{mg}$ values.
Full time series plots at locations NC02 and GE05 are shown in Figure 4.63. Location NC02 is located south of Norman's Cay in a gap along the margin of the Exuma chain bordering Exuma Sound and show prominent spikes in absorption values in the spring months of several years. Location GE05 is located on the same margin farther south just to the east of Great Exuma Island. This location is not near a gap in the Exuma chain and therefore is not exposed to periodic pulses of higher-absorption water such as those described in Chapter 3. This is evident in Figure 4.63 where few if any significant absorption pulses are seen at GE05 compared to NC02.

**Figure 4.63** Time series of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ at Norman's Cay (NC02) and Great Exuma (GE05) in the Bahamas. Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for NC02 are shown in plots A and B respectively and values for GE05 are in plots C and D. Grayed areas indicate winter.
4.3.1.9 Panama

Time series data were extracted at 19 locations in three different water bodies near Panama, the Caribbean Sea, Gulf of Panama, and Gulf of Chiriqui, shown in Figure 4.64. Mean values of aCDOM(443) and aph(443) are shown in Figures 4.65 and 4.66 respectively, along with the extent of the seasonal cycle and uncertainties at each location.

Figure 4.64 Locations with extracted time series data in Panama. Colors represent mean values of aCDOM(443) over the entire time series. Locations with plotted data are circled in yellow. Reefs are in orange and mangroves in green.
Figure 4.65 Values of $a_{CDOM}(443)$ for all locations in Panama. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle (MAC$_{rng}$), and black bars represent the uncertainty of the MAC$_{rng}$ values.

Figure 4.66 Values of $a_{ph}(443)$ for all locations in Panama. Blue squares represent the time series mean at each location, Red bars represent the range of the seasonal cycle (MAC$_{rng}$), and black bars represent the uncertainty of the MAC$_{rng}$ values.
Note the difference in absorption properties between locations in the Gulf of Panama compared with those in the Gulf of Chiriqui. Locations in the Gulf of Panama have higher overall absorption values and higher ranges of the seasonal cycles of both $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$. Full time series plots of locations in each water body are compared in Figure 4.67. This same trend in absorption properties is visible in the full time series as large peaks in absorption during the winter months in the Gulf of Panama, which are absent in the Gulf of Chiriqui. The difference is also visible in imagery, as seen in the MODIS image from 28 December 2004 shown in Figure 4.68, which shows the contrast between the two areas. This pattern is due to wind-induced upwelling in the wintertime in the Gulf of Panama, which is not observed in the Gulf of Chiriqui (D'Croz and O'Dea 2007).

Figure 4.67 Time series of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ at locations CHI04 and PAN03 in Panama. Values of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ for CHI04 are shown in plots A and B respectively and values for PAN03 are in plots C and D. Grayed areas indicate the boreal (Northern Hemisphere) winter, when upwelling is observed in the Gulf of Panama (PAN03), but not in the Gulf of Chiriqui (CHI04).
4.3.2 Time-series results of all reef areas

Time-series data from all 323 locations in all regions are shown in Figures 4.69-4.73. Figure 4.69 shows mean values of $a_{\text{CDOM}}(443)$ over the entire time series. Figure 4.70 shows the percentage of absorption (excluding that of pure water) at 443nm due to CDOM. Figure 4.71 shows values of total absorption (excluding that of pure water), which is the sum of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$. Figures 4.72 and 4.73 show values of the range of the seasonal cycles of $a_{\text{CDOM}}(443)$ and $a_{\text{ph}}(443)$ respectively. Note that maps in each panel are not at the same spatial scales.
Figure 4.69 Mean values of $a_{\text{CDOM}}(443)$ over full time series at all location (N=323). Scale of maps is not consistent. Coastal regions in the GBR indicated by numbers 1-4 are discussed in Section 4.4.
Figure 4.70 Percentage of absorption due to CDOM at 443nm at all locations (N=323). Scale of maps is not consistent. Coastal regions in the GBR indicated by numbers 1-4 are discussed in Section 4.4.
Figure 4.71 Mean values of total absorption \( [a_{\text{CDOM}}(443) + a_{\text{ph}}(443)] \) over full time series at all locations (N=323). Scale of maps is not consistent.
Figure 4.72 Range of the seasonal cycle (MAC) of $a_{CDOM}(443)$ at all locations (N=323). Scale of maps is not consistent.
Figure 4.73 Range of the seasonal cycle (MAC) of $a_{ph}(443)$ at all locations (N=323). Scale of maps is not consistent.
4.3.3 Hydrolight simulation results

Typical minimum and maximum values of the seasonal cycles of $a_{\text{CDOM}(443)}$ and $a_{\text{ph}(443)}$ found in each region are shown in Table 4.5 and were used as input values for Hydrolight simulations. The two absorption regimes in each region will be referred to as the "high" absorption regime (maximum value of the seasonal cycle) and the "low" absorption regime (minimum value of the seasonal cycle). Results of the Hydrolight simulations are presented in Table 4.6. For the "high" and "low" absorption regimes in each region, the UV/PAR ratio is shown along with the percentage of UVR present at a depth of 5m. Plots of downwelling irradiance spectra for "low" and "high" absorption regimes in the GBR lagoon are shown in Figures 4.74 and 4.75. The spectra of downwelling irradiance shown here are a measure of the intensity and spectral nature of incident light at several different depths. Note how downwelling irradiance values are nearly identical in the red end of the spectrum (600-700nm) for the "low" and "high" regimes. This is due to the fact that absorption due to water dominates the overall absorption budget at these wavelengths. However, large differences are observed between the two regimes at the blue end of the spectrum, particularly the UV region, which is shown by dotted lines. In the blue and UV portions of the spectrum, absorption is primarily controlled by absorption due to CDOM, which is visible in Figure 4.75, where increased CDOM absorption at 443nm in the "high"regime ($0.075\text{m}^{-1}$ compared to $0.016\text{m}^{-1}$ in the "low" regime) reduces the downwelling irradiance at all subsurface depths in the UV portion of the spectrum.
Table 4.5 Minimum and maximum values of $a_{\text{CDOM}(443)}$, $a_{\text{ph}(443)}$, and $[\text{Chl}]_{\text{Card}}$ in each region. Values in parentheses are chlorophyll concentrations calculated from $a_{\text{ph}(443)}$ using the relationship from Carder et al. (1999).

<table>
<thead>
<tr>
<th>Region</th>
<th>$a_{\text{CDOM}(443)}$ Low</th>
<th>$a_{\text{CDOM}(443)}$ High</th>
<th>$a_{\text{ph}(443)}$ ([Chl]) Low</th>
<th>$a_{\text{ph}(443)}$ ([Chl]) High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahamas</td>
<td>0.006</td>
<td>0.030</td>
<td>0.004 (0.031)</td>
<td>0.02 (0.21)</td>
</tr>
<tr>
<td>Bali</td>
<td>0.010</td>
<td>0.050</td>
<td>0.010 (0.088)</td>
<td>0.04 (0.58)</td>
</tr>
<tr>
<td>GBR (lagoon)</td>
<td>0.016</td>
<td>0.075</td>
<td>0.009 (0.078)</td>
<td>0.03 (0.38)</td>
</tr>
<tr>
<td>GBR (reef matrix)</td>
<td>0.008</td>
<td>0.040</td>
<td>0.010 (0.088)</td>
<td>0.04 (0.58)</td>
</tr>
<tr>
<td>FL Keys</td>
<td>0.008</td>
<td>0.050</td>
<td>0.007 (0.058)</td>
<td>0.03 (0.38)</td>
</tr>
<tr>
<td>Maldives</td>
<td>0.006</td>
<td>0.045</td>
<td>0.009 (0.078)</td>
<td>0.04 (0.58)</td>
</tr>
<tr>
<td>Palau and Yap</td>
<td>0.003</td>
<td>0.011</td>
<td>0.004 (0.031)</td>
<td>0.02 (0.21)</td>
</tr>
<tr>
<td>Panama (Gulf of)</td>
<td>0.020</td>
<td>0.180</td>
<td>0.017 (0.170)</td>
<td>0.12 (2.67)</td>
</tr>
<tr>
<td>Panama (Chiriqui)</td>
<td>0.009</td>
<td>0.044</td>
<td>0.011 (0.099)</td>
<td>0.05 (0.81)</td>
</tr>
<tr>
<td>Philippines</td>
<td>0.004</td>
<td>0.070</td>
<td>0.006 (0.049)</td>
<td>0.05 (0.81)</td>
</tr>
<tr>
<td>Thailand (Andaman)</td>
<td>0.011</td>
<td>0.240</td>
<td>0.016 (0.160)</td>
<td>0.35 (9.21)</td>
</tr>
<tr>
<td>Thailand (Gulf of)</td>
<td>0.012</td>
<td>0.150</td>
<td>0.012 (0.110)</td>
<td>0.11 (2.39)</td>
</tr>
</tbody>
</table>

Table 4.6 Hydrolight modeled UV/PAR ratios and % of surface UV irradiance at 5m depth for high and low absorption conditions in each region.

<table>
<thead>
<tr>
<th>Region</th>
<th>UV/PAR (5m) Low</th>
<th>UV/PAR (5m) High</th>
<th>% surface UV (5m) Low</th>
<th>% surface UV (5m) High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahamas</td>
<td>0.17</td>
<td>0.11</td>
<td>73%</td>
<td>44%</td>
</tr>
<tr>
<td>Bali</td>
<td>0.16</td>
<td>0.08</td>
<td>61%</td>
<td>27%</td>
</tr>
<tr>
<td>GBR (lagoon)</td>
<td>0.14</td>
<td>0.06</td>
<td>60%</td>
<td>19%</td>
</tr>
<tr>
<td>GBR (reef matrix)</td>
<td>0.15</td>
<td>0.09</td>
<td>65%</td>
<td>32%</td>
</tr>
<tr>
<td>FL Keys</td>
<td>0.16</td>
<td>0.08</td>
<td>70%</td>
<td>29%</td>
</tr>
<tr>
<td>Maldives</td>
<td>0.16</td>
<td>0.09</td>
<td>72%</td>
<td>30%</td>
</tr>
<tr>
<td>Palau and Yap</td>
<td>0.17</td>
<td>0.15</td>
<td>78%</td>
<td>62%</td>
</tr>
<tr>
<td>Panama (Gulf of)</td>
<td>0.13</td>
<td>0.01</td>
<td>53%</td>
<td>2%</td>
</tr>
<tr>
<td>Panama (Chiriqui)</td>
<td>0.16</td>
<td>0.09</td>
<td>67%</td>
<td>28%</td>
</tr>
<tr>
<td>Philippines</td>
<td>0.17</td>
<td>0.06</td>
<td>76%</td>
<td>18%</td>
</tr>
<tr>
<td>Thailand (Andaman)</td>
<td>0.15</td>
<td>0.003</td>
<td>63%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Thailand (Gulf of)</td>
<td>0.15</td>
<td>0.02</td>
<td>63%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>
Figure 4.74 Plots of Hydrolight simulated downwelling irradiance ($E_d$) spectra for the "low" absorption regime in the Great Barrier Reef lagoon. Dashed segments of spectra represent UV wavelengths.

Figure 4.75 Plots of Hydrolight simulated downwelling irradiance ($E_d$) spectra for the "high" absorption regime in the Great Barrier Reef lagoon. Dashed segments of spectra represent UV wavelengths.
4.4 DISCUSSION

The overall level of absorption due to CDOM and phytoplankton at any particular reef location is closely tied to the proximity of that location to sources of colored material and nutrients that can enter nearby waters, either by freshwater runoff or wind-induced upwelling. For example, the clearest waters in terms of absorption properties encountered in this study are those around the islands of Palau and Yap, which are far from any significant sources of colored material that can enter the water, aside from local sources, which are small due to the relatively limited surface area of each island. The Great Barrier Reef, rather, lies along a continental margin and is exposed to water rich in CDOM from nearby watersheds that are delivered to the GBR via rivers. Within the GBR, locations farther offshore within the reef matrix have lower levels of absorption than locations closer to shore. Even along the inshore portion of the GBR lagoon, CDOM absorption levels are variable, which can be seen in Figure 4.69 in the coastal regions marked with numbers 1, 2, and 3. Region 1 is known as the wet tropics where rainfall is relatively high and constant from year to year (Furnas 2003). Region 2 is near Townsville, where the outer matrix of reefs is less dense than in other parts of the GBR. This is visible as more offshore or oceanic waters with low overall absorption levels impinge onto the continental shelf and move into the lagoon. Region 3 is located near Mackay and is an area where the reef matrix is relatively dense and offshore waters do not regularly impinge on the continental shelf. Region 4 is near Heron Island and lies within a pocket of low absorption values even though it is close to shore. This pocket of low absorption is created by a deflection the northward flowing coastal current around
Fraser Island (Fig 4.21), as well as a lack of freshwater inputs in the area compared to region 3 which lies just to the north.

At all locations worldwide, the lowest overall values of absorption were found near the islands of Palau and Yap, in the oceanic locations surrounding the Philippines, and in locations adjacent to the Atlantic Ocean in the Bahamas. (Figure 4.69). The highest overall absorption values are found in the waters of Thailand, both in the Gulf of Thailand and the Andaman Sea, as well as near Panama. Both Thailand and Panama are areas of seasonal wind-induced upwelling, which increases absorption levels during certain times of the year. Note in Figure 4.69 the two locations in the Andaman Sea with lower CDOM absorption compared to locations to the north and south. These locations were discussed in Section 4.3.1.2 and are sheltered from northeast winds during the months of November through April, leading to reduced upwelling and lower overall absorption levels.

A comparison of the relative contributions to overall absorption by CDOM and phytoplankton can be seen in Figure 4.70, which shows the percentage of absorption (excluding pure water, which is constant in all locations) due to CDOM. On the GBR, locations closer to shore have a higher percentage of absorption due to CDOM compared to locations in the reef matrix, particularly in the wet tropics region (Region 1) and the area near Mackay (Region 3). As with mean values of $a_{\text{CDOM}}(443)$ over the full time series, locations near Townsville and Heron Island show lower percentages of CDOM absorption (Regions 2 and 4) indicating clearer water with a more oceanic character in terms of CDOM absorption. The lowest values of CDOM absorption
percentages are found near Palau and Yap and around the perimeter of the Philippine archipelago.

Figure 4.71 shows values of the sum of $a_{\text{CDOM}(443)}$ and $a_{\text{ph}(443)}$, which can be thought of as total water column absorption at 443nm (excluding pure water). This represents the total filter of incoming sunlight due to absorbing compounds in the water column. The spatial pattern of total absorption is consistent with that of mean $a_{\text{CDOM}(443)}$ (Figure 4.68), with the highest absorption values found nearshore on the GBR, within the inner islands of the Philippines, in the Gulf of Thailand and Andaman Sea, and in Panama. The lowest values of total absorption are found near Palau and Yap, offshore of the reef matrix on the GBR, around the perimeter of the Philippines, and in the Bahamas.

The range of seasonal cycle in both $a_{\text{CDOM}(443)}$ and $a_{\text{ph}(443)}$ are shown in Figures 4.72 and 4.73 respectively. Locations with low values of $a_{\text{CDOM}(443)}$ tend to have lower ranges of their seasonal cycle, which is evident in locations such as Palau and Yap, the Bahamas, the perimeter of the Philippines, and the outer reef matrix of the central GBR. This trend is also evident in the plots of mean $a_{\text{CDOM}(443)}$ and seasonal cycle ranges for individual regions presented in Section 4.2, where locations with low $a_{\text{CDOM}(443)}$ values tending to have lower seasonal cycle ranges. Overall, ranges of seasonal cycles in $a_{\text{ph}(443)}$ tend to be less than ranges in $a_{\text{CDOM}(443)}$ as can be seen by comparing Figures 4.72 and 4.73, which both have identical scales for marker colors at each location.
Variability is driven by different processes in different locations. The GBR is a complex system where absorption values are determined by proximity to shore and the inflow of oceanic water into the reef matrix due to the East Equatorial Current colliding with the Australian continent as well as tidal mixing across the continental shelf. Locations close to shore in the lagoon, which were not assessed in this study due to shallow water, are exposed to highly colored waters from terrestrial runoff which can become entrained in the northward flowing coastal current on the GBR, which is driven by the prevailing southeasterly tradewinds. In both the Gulf of Thailand and Andaman Sea, variability in absorption properties appears to be driven by wind-driven upwelling during the winter months and coincides with spikes in both CDOM and phytoplankton absorption and not the rainy season on the Thai peninsula. Absorption variability in the Philippines is somewhat similar to that of the GBR, in that areas exposed to oceanic water from the Pacific Ocean and South China Sea have lower absorption values than locations within the inner islands of the archipelago. Palau and Yap, which are not near any large sources of colored material, have the lowest values of both absorption and seasonal cycle range encountered at any location. In the Maldives, temporal variability in some locations is due to the reversal of currents with phases of the Asian monsoon.

One way to get a broad sense of the variability in absorption properties on a global scale is to compare the two absorption regimes in Table 4.5. The "low" regime represents the lowest absorption levels that a given region might be exposed to during a typical year, and the "high" regime represents the opposite. At all locations, $a_{\text{CDOM}}(443)$ values of the "low" regime ranged from $0.003 \text{m}^{-1}$ to $0.02 \text{m}^{-1}$, while in the "high" regime, values ranged from $0.011 \text{m}^{-1}$ to $0.24 \text{m}^{-1}$ (Table 4.5). This indicates that reef regions
worldwide have a relatively uniform "baseline" of low absorption conditions encountered at some point during the year, and that the main differences between regions are due to periods when peaks in absorption that occur, whether due to runoff, upwelling, or some other factor.

The effects of absorption variability on the underwater light field can be seen in Table 4.6. Elevated UV/PAR ratios as well as the percentage of surface UV at 5m are associated with the "low" absorption regime. As with absorption values, greater variability is seen between regions in the "high" regime compared to the "low" regime. Palau and Yap have small differences between the two regimes, while in other regions such as Thailand and the Gulf of Panama, the differences are substantial.

The potential connections between the variability in absorption properties and episodes of coral bleaching will be examined in the next chapter.
5. AN EXAMINATION OF THE RELATIONSHIP BETWEEN OCEAN COLOR PARAMETERS AND EPISODES OF CORAL BLEACHING

5.1 INTRODUCTION

5.1.1 Coral bleaching

The following section provides an introduction to coral bleaching. For a more complete discussion of bleaching, please see Hough-Guldberg (1999), or van Oppen and Lough (2009). Coral bleaching is a response to environmental stressors by corals which results in a breakdown of the coral-algal symbiosis and the expulsion of endosymbiotic dinoflagellates from coral tissues. This "whitening" of coral tissues, which can result in mortality, was first recognized as major global phenomenon in the early 1980's (Oliver et al. 2009). The first extensively documented global coral-reef bleaching event was in 1982-1983 (Oliver et al. 2009 and references therein). Since then, periodic bleaching events have occurred at local, regional and global scales, often resulting in mortality (Fitt et al. 2001).

The most common environmental factor associated with episodes of coral bleaching is elevated seawater temperature (Hough-Guldberg 1999, Dunne and Brown 2001). Underlying this response to elevated temperatures is oxidative stress, which is caused by the accumulation of reactive oxygen species (ROS) such as superoxide radicals, singlet oxygen, hydrogen peroxide, and hydroxide radicals, which can cause
damage to molecules like lipids, proteins, and DNA, which are critical for cellular functions (Lesser 2011).

The exact physiological mechanisms that lead to coral bleaching are not completely understood. Early laboratory studies examined damage to photosystem II (PSII) of the photosynthetic apparatus in symbiotic algal cells, which resulted in photoinhibition of zooxanthellae, manifested by a decrease in net photosynthesis. In addition to photoinhibition, the production of ROS was also observed. The causes of photoinhibition were attributed to increased seawater temperatures (Igelsias-Prieto et al. 1992), exposure to high levels of visible radiation (Hough-Guldberg and Smith 1989), exposure to UVR (Lesser and Shick 1989), and to UVR exposure combined with elevated seawater temperatures (Lesser 1996, 1997). More recent studies have shown that the D1 protein within the PSII apparatus is the principal site of damage during exposure to thermal stress and solar radiation (Warner et al. 1999, Lesser and Farrell 2004).

Another mechanism has been proposed, which involves the nutritional status and growth rates of zooxanthellae (Wooldridge et al. 2009b). The study proposes that the breakdown of the coral-algal symbiosis begins with an initial partial expulsion of zooxanthellae caused by exposure to high levels of irradiance. Following the initial loss of algal cells, the remaining zooxanthellae retain photosynthetic carbon for growth required to replace cells lost in the initial expulsion, rather than passing on that photosynthate to the coral host. This reduction in photosynthate available to the host has potential implications for threshold limits for coral bleaching (Wooldridge 2009b). It also is a potential explanation for evidence that upper bleaching thresholds tend to be lower and bleaching damage greater in reef areas that are exposed to higher levels of
nutrient inputs, either through terrestrial runoff or the upwelling of water from deeper regions (D'Croz et al. 2001, Wooldridge 2009a, Wagner et al. 2012).

It is clear from both field and laboratory studies that elevated seawater temperatures, combined with exposure to high levels of solar radiation, both visible and UV, are causal factors in coral bleaching (Fitt et al 2001). One way to assess a potential role that water-column absorption of solar radiation might play in coral bleaching is to examine the absorption conditions present during time periods when bleaching was observed. Hallock et al. (2006) and Ayoub et al. (2012) found that levels of absorbing compounds such as CDOM in the water column can impact the synergistic effects of solar radiation and thermal stress. If water column absorption is lower than normal during a period of thermal stress, it could exacerbate stress to corals by exposing them to higher than normal levels of solar irradiance. However, if water column absorption is higher than normal during a period of thermal stress, light stress could be alleviated by a reduction in solar irradiance due to increased absorption by compounds in the water column.

5.1.2 Effects of ENSO on coral bleaching

El Nino Southern Oscillation (ENSO) events are associated with rapid warming of the eastern tropical Pacific Ocean and have been shown to have a profound effect on episodes of mass coral bleaching and subsequent mortality with two of the most extensive and severe episodes of coral bleaching occurring during the 1982-83 and 1997-98 ENSO events (Wellington and Glynn 2007). ENSO effects on bleaching, however, vary widely among reef regions. For example, elevated seawater temperatures in the Indian Ocean basin are observed concurrently with ENSO warming in the eastern Pacific
(Baquero-Bernal et al. 2002), while elevated seawater temperatures on the Great Barrier Reef can occur up to one year prior to ENSO-related warming in the eastern Pacific (Lough 1994). In the eastern Coral Triangle region, near Papua New Guinea, thermal stress events are associated with the cooler La Niña ENSO phase (Penaflor 2009). The climate pattern is even more complex on the GBR due to a phenomenon called El Niño/La Niña Modoki, which refers to events that are similar to classic El Niño, but are associated with warming in the central equatorial Pacific rather than the eastern equatorial Pacific (Redondo-Rodriguez et al. 2011). Because the GBR is a large and complex system, traditional ENSO events and ENSO Modoki events affect seawater temperatures differently in different parts of the GBR, with traditional ENSO events having the greatest effect on seawater temperatures in the southern GBR and ENSO Modoki events having a greater effect in the northern GBR (Redondo-Rodriguez et al. 2011).

5.1.3 Bleaching in previously described coral reef regions

A complete discussion of historical bleaching records and patterns found in the Reefbase database of bleaching observations can be found in "Coral Bleaching in Space and Time" by Oliver et al. (2009). Brief descriptions of bleaching episodes observed in some of the reef regions defined in Chapter 4 are presented in the following sections. Definitions of bleaching severity associated with marker (circle) colors in Figures 5.1-5.4 are defined in Table 5.1.
5.1.3.1 Great Barrier Reef

Bleaching on the Great Barrier Reef has been observed since 1931, but the first mass bleaching event with a well-documented extent and duration occurred in 1982-1983. More recently, two very severe events occurred during the Austral (Southern Hemisphere) summers in 1998 and 2002, when bleaching was observed throughout the GBR. While extensive areas were reported to have bleached, bleaching was not uniform in space and time (Berkelmans et al. 2004). Shallow inshore reefs were much more extensively bleached during both the 1998 and 2002 events. Bleaching was not as severe in the outer matrix of reefs, but was present in some areas and not in others (Berkelmans et al. 2004). Figure 5.1 shows observations of bleaching on the GBR during the 1998 and 2002 events. While elevated seawater temperatures are associated with bleaching observations during the two events, there are exceptions where no bleaching was observed on reefs exposed to elevated temperatures and also areas where bleaching was observed on reefs not exposed to elevated temperatures (Berkelmans et al. 2004). Bleaching was observed during 2006 on the GBR, but bleaching was not severe in nature and was limited to a few locations.
Bleaching observations on the Great Barrier Reef during 1998 and 2002. Bleaching observations are from the Reefbase dataset. Reefs are in orange and mangroves in green. Markers (circles) of bleaching observations are coded by color and represent bleaching severity as defined in Table 5.1.

5.1.3.2 Thailand

Reefs in Thailand have experienced several coral-bleaching episodes, but different areas have been affected at different times. Bleaching and mortality during episodes in 1991 and 1995 were severe and widespread in the Andaman Sea, but were not observed in the Gulf of Thailand (Yeemin et al. 2001). However, bleaching during the 1998 event was much more severe in the Gulf of Thailand, where bleaching had never been previously observed (Spalding et al. 2001, Chou et al. 2002). Bleaching locations in Thailand during the 1998 event are shown in Figure 5.2.
The reefs near Phuket, which have adapted to high levels of sedimentation, have been extensively studied since the 1980's and observations of bleaching have been recorded in 1991, 1993, 1997, 1998, 2002, and 2010 (Reefbase bleaching observation dataset). Several studies of bleaching and its causes have been centered around the reefs of Phuket (Brown et al. 1994, Dunne and Brown 1996, Le Tissier and Brown 1996, Dunne and Brown 2001), particularly annual incidents of solar-induced bleaching affecting the upward, west-facing surfaces of massive corals, such as *Goniastrea aspera* (Brown et al. 1994, Le Tissier and Brown 1996).

**Figure 5.2** Bleaching observations in Thailand during 1998. Bleaching observations are from the Reefbase dataset. Reefs are in orange and mangroves in green. Markers (circles) of bleaching observations are coded by color and represent bleaching severity as defined in Table 5.1.
5.1.3.3 The Philippines

The only episode of mass coral bleaching in the Philippines occurred from early June until late November 1998, starting in the northern portion of the country and moving in a roughly counter-clockwise pattern (Arceo 2001). Locations of bleaching observations in the Philippines during the 1998 event are shown in Figure 5.3.

Figure 5.3 Bleaching observations in the Philippines during 1998. Bleaching observations are from the Reefbase dataset. Reefs are in orange and mangroves in green. Markers (circles) of bleaching observations are coded by color and represent bleaching severity as defined in Table 5.1.
5.1.3.4 Panama

Reefs in Panama were bleached severely during the ENSO event of 1997-98 (Glynn et al. 2001). However, bleaching was not uniform due to different upwelling regimes in the Gulf of Panama compared to the Gulf of Chiriqui. Seasonal upwelling during the winter in Panama is wind-driven and occurs as a result of winds blowing through topographic depressions in the isthmus of Panama. The Gulf of Panama is affected by this seasonal upwelling, while the Gulf of Chiriqui is not (D'Croz and O'Dea 2007). Locations of bleaching observations in Panama during the 1998 event are shown in Figure 5.4. Note in Figure 5.4 that bleaching was much more widespread in the gulf of Chiriqui, which had six observations of severe bleaching, compared to only one in the Gulf of Panama.

![Figure 5.4](image)

**Figure 5.4** Bleaching observations in Panama during 1998. Bleaching observations are from the Reefbase dataset. Reefs are in orange and mangroves in green. Markers (circles) of bleaching observations are coded by color and represent bleaching severity as defined in Table 5.1.
5.3 METHODS

5.3.1 Time series of satellite ocean color data

The same methods for constructing and analyzing time series of ocean color parameters described in section 4.3.1 are used here.

5.3.2 Coral reef bleaching observations

To examine episodes of coral bleaching for comparison with ocean color parameters, the ReefBase dataset of bleaching observations was used. This database is maintained by the WorldFish Center through the ReefBase organization and is available in several formats from www.reefbase.org. This dataset contains the most comprehensive archive of coral-beaching records and has observations dating from 1983 through the present (Oliver et al. 2009). The dataset includes virtually all coral bleaching observations published in the scientific literature, along with unpublished reports from a variety of organizations, including the National Oceanic and Atmospheric Administration (NOAA), Coral Reef Watch (http://coralreefwatch.noaa.gov), and NOAA's Coral Health and Monitoring Network (http://coral.aoml.noaa.gov) (Oliver et al 2009).

Observations of bleaching found in the dataset have a minimum set of information for each observation, which includes the date of observation, location, an assessment of the severity of bleaching observed, and the source of information. For some observations, water depth, coral species affected, and some quantitative information pertaining to the percentage of coral affected is included, although the majority of observations do not include this information (Oliver et al. 2009). For the sake of consistency, only the minimum information about bleaching at each site of interest was included for bleaching
observations used in this study, which is given in Table 5.1.

**Table 5.1** Categories of coral bleaching found in the ReefBase dataset. Colors in parentheses are the colors used to represent bleaching severity on maps in Figures 5.1-5.4.

<table>
<thead>
<tr>
<th>Bleaching code</th>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (green)</td>
<td>No bleaching</td>
<td>No bleaching observed</td>
</tr>
<tr>
<td>-1 (gray)</td>
<td>Bleaching (severity unknown)</td>
<td>Bleaching observed with no information on severity</td>
</tr>
<tr>
<td>1 (blue)</td>
<td>Mild bleaching</td>
<td>Up to 10% of coral cover bleached</td>
</tr>
<tr>
<td>2 (yellow)</td>
<td>Moderate bleaching</td>
<td>10-50% of coral cover bleached</td>
</tr>
<tr>
<td>3 (red)</td>
<td>Severe bleaching</td>
<td>Over 50% of coral cover bleached</td>
</tr>
</tbody>
</table>

5.3.3 Anomalies of $a_{\text{CDOM}(443)}$, $a_{\text{ph}(443)}$, and sea-surface temperature

To examine the role that absorption anomalies might play in episodes of coral bleaching, cumulative anomalies of CDOM and phytoplankton absorption were calculated by integrating the difference between $a_{\text{CDOM}(443)}$ and $a_{\text{ph}(443)}$ and their respective seasonal cycles during time periods when bleaching was observed in each region. To assure consistency between regions, summed differences were normalized by the number of time bins summed to create the difference. To examine the relationship between thermal stress and light stress, anomalies of sea-surface temperature were also computed for the same time periods.
5.3.4 Meteorological data for the Philippines and Florida Keys

Rainfall data from 1998-2010 in Manila, Philippines, were obtained from the Philippine Atmospheric Geophysical and Astronomical Service Administration at http://www.pagasa.dost.gov.ph/. Wind and cloudcover data from the Philippines were obtained for the time period 1998-2010 from Weather Underground at www.wunderground.com/history/airport/RPLL/2012/11/12/CustomHistory.html. Florida Keys rainfall data during 1998 were obtained from the Florida Climate Center at http://climatecenter.fsu.edu/products-services/data.

5.4 RESULTS

Anomalies of SST and $a_{CDOM}(443)$ calculated for all locations during bleaching periods during 1998 are shown in Figures 5.5 and 5.6. For SST, negative anomalies are indicated by black diamonds, while green (weak), yellow (moderate), red (strong), and white (extreme) diamonds indicate positive anomalies. Positive SST anomalies indicate higher than normal temperatures and therefore thermal stress on corals. For $a_{CDOM}(443)$, negative anomalies are indicated by white (strong), red (moderate), and yellow (weak) diamonds, while green (weak), blue (moderate), and black (strong) diamonds indicate positive anomalies. Negative anomalies of $a_{CDOM}(443)$ indicate lower than normal absorption and increased light stress on corals.
Figure 5.5 Anomalies of sea-surface temperature during periods of coral bleaching in 1998 in all locations (N=323). Anomalies were calculated by summing the differences between SST and its seasonal cycle during bleaching periods.
Figure 5.6 Anomalies of $a_{\text{CDOM}}(443)$ during periods of coral bleaching in 1998 in all locations (N=323). Anomalies were calculated by summing the differences between $a_{\text{CDOM}}(443)$ and its seasonal cycle during bleaching periods.
In terms of bleaching, all regions bleached to some extent during 1998, with the exception of Yap, which bleached very little. The relationship between bleaching and positive SST anomalies is seen in Figure 5.5, where positive anomalies are observed in all regions. Negative SST anomalies are only seen in four locations in the far northern GBR and central Philippines. Anomalies of a_{CDOM}(443) were mostly negative during episodes of coral bleaching during 1998 as seen in Figure 5.6. The only region to have consistently positive a_{CDOM}(443) anomalies in 1998 was the Florida Keys, which was due to a wetter than normal winter and spring in Florida in 1998.

Mean values of anomalies of a_{CDOM}(443), a_{ph}(443), and SST for all locations and the GBR in 1998 and 2002 are given in Table 5.2. Note that SST anomalies were strongly positive during 1998, but only moderately positive in 2002. On the GBR, however, strongly positive SST anomalies were seen in both 1998 and 2002. In terms of absorption, a_{CDOM}(443) anomalies were negative in both 1998 and 2002, both on the GBR and worldwide. Worldwide, anomalies of a_{ph}(443) were positive in 1998 and negative in 2002, but were positive during both years on the GBR.

Table 5.2 Mean values of cumulative a_{CDOM}(443) and SST anomalies for all locations and for the Great Barrier Reef only during periods in 1998 and 2002 when bleaching was observed. Anomalies were calculated by summing the differences between SST and aCDOM and their respective seasonal cycles during bleaching periods.

<table>
<thead>
<tr>
<th>Region</th>
<th>a_{CDOM}(443) 1998</th>
<th>a_{CDOM}(443) 2002</th>
<th>a_{ph}(443) 1998</th>
<th>a_{ph}(443) 2002</th>
<th>SST 1998</th>
<th>SST 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>All locations</td>
<td>-0.046</td>
<td>-0.012</td>
<td>0.014</td>
<td>-0.007</td>
<td>10.05</td>
<td>2.17</td>
</tr>
<tr>
<td>GBR only</td>
<td>-0.007</td>
<td>-0.025</td>
<td>0.006</td>
<td>0.017</td>
<td>7.17</td>
<td>9.15</td>
</tr>
</tbody>
</table>
Coral bleaching was severe and widespread in the Philippines during 1998, which was accompanied by strongly positive SST anomalies and strongly negative anomalies of $a_{\text{CDOM}}(443)$ as seen in Figures 5.5 and 5.7. The full time series of data at location APO01 is plotted in Figure 5.8, with grayed areas indicating the time period of bleaching in 1998. Levels of $a_{\text{CDOM}}(443)$ during the bleaching period are the lowest found in the entire record, while SST reaches its highest level during the bleaching period. Rainfall was very low from late spring into summer 1998 in the Philippines as seen in Figure 5.9, which explains the reduction in CDOM absorption values during that time. Cloud cover and winds were also low during this time, indicating doldrum conditions, which could lead to
an increase in SST and a further reduction in $a_{\text{CDOM}(443)}$ due to photobleaching of CDOM in overlying waters.

Figure 5.8 Time series plots of $a_{\text{CDOM}(443)}$ and sea-surface temperature (SST) at location APO01. Time series data are shown in blue and seasonal cycles in red. Grayed areas in each plot represent the coral bleaching episode in 1998.
Figure 5.9 Rainfall in Manila, Philippines in the late spring (Apr-Jun) and late summer (July-Sep). Red line (July-Sep) is the rainy season in the Philippines.

In Panama, previously described differences between locations in the Gulf of Panama compared to the Gulf of Chiriqui are seen clearly in bleaching observations as well as anomalies of $a_{\text{DOM}}(443)$ and SST, as shown in Figure 5.10. Wind-driven upwelling causes large differences in absorption values and SST as seen in a comparison of locations SAB01 (Gulf of Panama) and SIL01 (Gulf of Chiriqui) in Figure 5.11. Note in Figure 5.11 that SST is above normal in both locations during the time of bleaching, but reaches approximately 31°C in the Gulf of Chiriqui, but only 29°C in the Gulf of Panama. Bleaching was much more severe in 1998 in the Gulf of Chiriqui compared to the Gulf of Panama, as seen from bleaching observations in Figure 5.11 (circles).
Figure 5.10 Locations of bleaching observations (circles) and anomalies of $a_{\text{CDOM}}(443)$ (diamonds) in Panama in 1998. Reefs are in orange and mangroves in green.
Figure 5.11 Time series plots of $a_{\text{DOM}}(443)$ and sea-surface temperature (SST) at two locations in Panama. Location SAB01 is located in the Gulf of Panama and is shown in plots A and B. Location SIL01 is located in the Gulf of Chiriqui and is shown in plots C and D. Note the difference in y-axis scaling for plots A and C. Grayed areas in each plot represent coral bleaching episode in 1998.

The difference between the two locations is seen clearly in Figure 5.12, which shows a SeaWiFS satellite image of $a_{\text{DOM}}(443)$ from 29 January 1998, just prior to the onset of bleaching. Levels of $a_{\text{DOM}}(443)$ are on the order of 0.015 m$^{-1}$ in the Gulf of Chiriqui and range from 0.05 m$^{-1}$ to 0.4 m$^{-1}$ in the Gulf of Panama.
Figure 5.12 SeaWiFS image of Panama from 29 January 1998, just prior to the onset of the 1998 mass bleaching event. Locations SIL01 and SAB01 are marked by red circles.

5.5 DISCUSSION

The results of this portion of the study support the many prior observations that positive anomalies of SST are associated with episodes of coral bleaching. However, the data indicate that negative anomalies of $a_{\text{CDOM}}(443)$ are also associated with bleaching episodes. This suggests that coral bleaching may be the result of a synergy between warmer than normal temperatures and lower than normal water-column absorption, leading to a combination of thermal stress and light stress to which corals are exposed. This mechanism has been proposed in several previous studies (Lesser 1996, Warner et al. 1999, Lesser and Farrell 2004) and is confirmed by this study. It seems likely that
doldrum conditions may be a precursor to bleaching episodes, given that both thermal stress and light stress on corals may increase during times of low winds and low cloud cover, allowing more sunlight to penetrate the water column, leading to increased temperatures and increased light stress. In addition, CDOM in the water column during a period of doldrum conditions may be degrade photochemically, thereby reducing its capacity to absorb light (Zepp et al. 2008).

The results of this study also point to the importance of ultraviolet radiation in episodes of coral bleaching. As shown in Table 5.2, time periods when bleaching was observed in various regions are associated with negative anomalies of $a_{\text{CDOM}}(443)$, but not $a_{\text{ph}}(443)$, indicating that UV light stress may be more of a causal factor for coral bleaching, compared to PAR light stress because negative anomalies of $a_{\text{CDOM}}(443)$ affect underwater irradiances in the UV much more than in the visible portion of the light spectrum, as discussed in Section 4.3.3 (Williams and Hallock 2004 and references therein). Globally, ultraviolet radiation incident upon the sea surface was at a maximum on in 1998 due to maximal atmospheric ozone depletion that year (Jones et al. 2009). High levels of incident UVR increase light stress and likely are a contributing factor to such widespread bleaching in 1998.

A possible explanation for the difference in observed bleaching between the islands of Palau and Yap described in Chapter 1 can be seen in Figures 5.5 and 5.6. The mean SST anomaly at all locations during the bleaching episode in Palau in 1998 was 16.8, compared to 10.7 in Yap, indicating that corals surrounding Palau were under more thermal stress than those around Yap. However, anomalies of $a_{\text{CDOM}}(443)$ were lower in Yap (-0.025) compared to Palau (-0.011). This indicates a difference between the two
islands in terms of thermal stress and light stress. Although the two islands are located relatively close to each other in the western Pacific, they are subject to different circulation patterns based upon the presence of the Palau Eddy, described in Section 4.2.1.5 and shown in Figure 4.9, which is present only in the summertime. This difference in circulation patterns could provide an explanation of the thermal and light stress differences observed between the two islands in 1998.
6. CONCLUSIONS AND FUTURE WORK

The results of this study can be summarized as follows:

- CDOM is the primary absorber of ultraviolet radiation in the clear waters of coral reef regions.
- Variations of water column absorption occur over spatial scales as small as a few meters and temporal scales as short as a few hours (Fig. 3.4).
- Variability of CDOM and phytoplankton absorption is driven by different processes in different reef regions and is related to local physical oceanographic conditions and proximity to sources of absorbing compounds.
- Variability in absorption due to CDOM and phytoplankton in coral reef regions has significant effects on the underwater light field and the levels of solar radiation, both UV and PAR, to which corals are exposed.
- Episodes of coral bleaching in 1998 and 2002 were associated with positive sea-surface temperature anomalies and negative CDOM absorption anomalies, indicating the presence of both thermal and light stress for corals.

In terms of future work, there are a number of avenues of research that could be conducted to expand on the research presented in this study. While this study included many reef regions throughout the world, it did not include a complete inventory of the world's reefs. Other reef regions that could be included are the eastern Coral Triangle, the
western Indian Ocean and Red Sea, the Mesoamerican Barrier Reef system near Belize and reefs in the eastern Pacific near Costa Rica and Honduras.

Another possible extension of this work is to incorporate water column absorption into satellite products used to predict future episodes of coral bleaching. Current products are based on sea-surface temperature. However, NOAA's Coral Reef Watch program recently added a Light Stress Damage product, available at http://coralreefwatch.noaa.gov/satellite/lsd/index.html. This experimental satellite-derived product attempts to estimate the combination of light stress and thermal stress on corals using a combination of sea-surface temperature and PAR products. Based on the results of this study, including an estimate of water-column absorption, particularly CDOM absorption would increase the accuracy of any satellite product designed to predict light stress on corals. Neglecting absorption due to CDOM underestimates potential damage to corals from exposure to UVR because PAR is a less robust indicator of UV stress than CDOM absorption.

It would also be valuable to examine anomalies of SST and water-column absorption during time periods prior to bleaching episodes. Several studies (Wooldridge 2009b, Hallock et al. 2006) have found that prior temperature and light conditions can have an effect on the susceptibility of reefs to future episodes of bleaching.

Aside from issues related to coral reefs or bleaching, satellite data provide valuable information about oceanographic conditions, circulation patterns, and variability of in-water constituents in areas throughout the world. Some areas are well studied, based on their importance to developed nations with well-established scientific institutions. However, other areas receive little attention due to their remote location or lack of
scientific infrastructure in nearby countries. A plethora of satellite data exists that is publicly available, but has never been examined in detail for many areas. A systematic examination of imagery and time series data in areas throughout the world can provide valuable insights into oceanographic conditions that have previously been overlooked.
LIST OF REFERENCES


APPENDICES
Appendix 1: Previously published material

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REPORT

Daniel B. Otis · Kendall L. Carder
David C. English · James E. Ivey

CDOM transport from the Bahamas Banks

Abstract The transport of colored dissolved organic matter (CDOM) between shallow banks and deep basins in the Bahamas was the focus of this study. Hydrographic and CDOM absorption measurements made on the Bahamas Banks and in Exuma Sound during the spring of 1999 and 2000 showed that values of salinity and CDOM absorption at 440 nm were higher on the banks (37.18 psu, 0.06 m$^{-1}$), compared to Exuma Sound (37.04 psu, 0.03 m$^{-1}$). Spatial patterns of CDOM absorption in Exuma Sound revealed that plumes of CDOM-rich water flow into Exuma Sound from the surrounding banks. These patterns were determined using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data processed using a Moderate Resolution Imaging Spectroradiometer (MODIS) algorithm to derive CDOM absorption estimates. These data, along with time-series data collected in a channel between the banks and sound, suggest that bank water rich in CDOM and salinity leaves the banks during ebb tide, whereas sound water, with lower levels of CDOM and salinity, extends onto the banks during flood tide. Because CDOM absorbs ultraviolet radiation, a causal factor of reef organism bleaching, we discuss the meaning of our findings in terms of susceptibility to coral bleaching in the Exuma region.

Keywords Coral bleaching · Exuma Sound · MODIS · Ocean color · SeaWiFS

Introduction Chromophoric or colored dissolved organic matter (CDOM), also known as gelbstoff, yellow matter, or gelvin, absorbs primarily ultraviolet and blue light and plays an important role in determining the underwater light field. In the open ocean, where coastal runoff and riverine input are negligible on annual time scales and chlorophyll $a$ concentrations ([Chl]) are typically less than 0.5 mg/m$^3$, CDOM absorption dominates the total attenuation budget and is the major factor controlling the penetration of ultraviolet radiation (UVR) (Nelson and Siegel 2002). In many coastal areas, the primary source of CDOM is freshwater input from terrestrial runoff. However, in subtropical bank regions such as the Bahamas that lack fluvial inputs, substrate-related sources, particularly seagrass beds and coral reefs, have been found to be the primary CDOM sources (Boss and Zaneveld 2003). Due to its absorptive properties, CDOM protects marine organisms from UVR, and, therefore, has an important role in marine photochemical and photobiological processes (Nelson and Siegel 2002). Because exposure to high levels of UVR has been implicated in the bleaching of reef-building corals (Glynn 1996), temporal and spatial patterns of CDOM could explain local variations in coral bleaching intensity.

The focus of this study is to examine the transport of CDOM between shallow banks and deep basins in the Bahamas. The Bahama Archipelago consists of vast carbonate banks (average depth ≤3 m) with islands, deep channels, and deep-water basins. The two basins, Tongue of the Ocean (TOTO) and Exuma Sound, are more than 1,000 m deep and are mostly enclosed by islands and shallow-water banks. Shallow-bank regions in the Bahamas are affected much more by latent and sensible heat fluxes to the atmosphere than are the deep basins due to the limited heat capacity of a shallow water column (Smith 1995). The difference in response of these two regions to solar heating and evaporation acts to create density gradients between the banks and the deep basins (Smith 1995).

For this study, a location was selected near Lee Stocking Island (LSI) in the chain of Exuma Cays. This thin chain of islands separates Exuma Sound from the Great Bahama Bank. A 1-year record of salinity and
Appendix 1: Previously published material (Continued)

Remote sensing

Most algorithms used to interpret ocean color measurements made from space involve taking spectral ratios of remote-sensing reflectance (Rrs) — upwelling radiance/downwelling irradiance) to estimate chlorophyll concentration (Chl). The algorithm used in the coastal zone color scanner (CZCS) and sea-viewing wide radiance/downwelling irradiance) to estimate chlorophyll concentration from SeaWiFS data are only valid in deep water. By examining CDOM absorption in deep water adjacent to the banks, export from the banks can be inferred.

Methods

Data for this study were collected around Lee Stocking Island in the Bahamas as part of the coastal benthic optical properties (CoBOP) experiment from 20 May until 3 June 1999 and from 17 May until 27 June 2000. Sampling locations included offshore sites in Exuma Sound, a tidal channel on the bank, and coral reef sites on the narrow shelf separating the Exuma chain of islands from Exuma Sound (Fig. 1). Measurements of wind speed and direction were collected at a meteorological station located on LSI during the experiment.

Measurements of salinity as well as CDOM absorption (a_CDOM) were made using a slow-drop optical instrument package. This package was slightly negatively buoyant and was deployed so as to profile slowly through the water column to a maximum depth of approximately 70 m. Instrumentation included a Falmouth Scientific Inc. 2'' Micro-CTD (pressure, conductivity, and temperature), and two WET Labs, Inc. ac-9 absorption meters (attenuation and absorption at wavelengths of 412, 440, 488, 510, 532, 555, 650, 676, and 715 nm). One ac-9 fitted with a 0.2-μm filter was used for dissolved absorption measurements. Data from the slow-drop instrument package were processed according to Ivey et al. (2002).

During CoBOP 2000, transect measurements were made several times a minute by pumping near-surface sea water through a 120-l insulated container while the ship was underway from Adderly Inlet to offshore sites in Exuma Sound (Fig. 1). Immersed in the container were a Falmouth Scientific Inc. 2'' Micro-CTD, a WET Labs Flashlamp Fluorometer (CDOM fluorescence), and three WET Labs, Inc. ac-9 absorption meters (attenuation and absorption at wavelengths of 412, 440, 488, 510, 532, 555, 650, 676, and 715 nm). One ac-9 fitted with a 0.2-μm filter was used for dissolved absorption measurements. Data from the slow-drop instrument package were processed according to Ivey et al. (2002).

During CoBOP 2000, seawater was pumped through the container at a rate of 17 to 25 l/min, providing a roughly 5-min flushing period. SeaWiFS data (1-km resolution) were processed to derive [Chl] and CDOM absorption using an algorithm developed by Carder et al. (1999), which can be parameterized for three bio-optical domains. For this study, the algorithm was tuned for an “un-packaged” regime, meaning an environment with a high fraction of photoprotective pigments and low self-shading by phytoplankton cells (Carder et al. 1999). This is appropriate for the clear waters of the Bahamas in the late spring. Level 1A SeaWiFS data collected by a High Resolution Picture Transmission receiving station located at the University of South Florida in St. Petersburg were processed on a Silicon Graphics workstation using the SeaWiFS Data Analysis System version 4.3.

Chlorophyll a concentrations used for comparison with satellite-derived values were determined fluorometrically (Holm-Hansen and Riemann 1978). Particulate absorption of surface water samples was determined using the quantitative filter pad technique (Truper and Yentsch 1967) with an optical path-length elongation factor (β) as discussed in Carder et al. (1999). Time series data collected during CoBOP 2000 in a tidally flushed channel (Fig. 1) are provided by Emmanuel Boss and Ron Zaneveld (2003).

Results and discussion

The a_CDOM(440)–salinity relationship obtained from both bank and shore sites in Exuma Sound (Fig. 1) during CoBOP 1999 and 2000 is similar to that found in the same study area by Boss and Zaneveld (2003). The positive correlation between these two quantities suggests a common source location of CDOM and salinity. Negative correlations between the two would be expected if the source of
CDOM was fresh water rich in CDOM, such as waters influenced by river runoff (e.g., Hu et al. 2003). In this area, however, with an absence of freshwater runoff, a positive correlation is consistent with our hypothesis that bank water is CDOM-rich and relatively saline-rich due to evaporation and primary production in the grass beds on the shallow banks. Warrior et al. (2002) show the effects of depth and bottom albedo on evaporation in the Bahamas, which result in enhanced salinity and density over the shallow banks. Absorption, due to CDOM and particulates, and salinity are much higher on the banks than in Exuma Sound (Table 1). The gradient between the two regions can also be easily seen in the transect data collected during CoBOP 2000 (Fig. 3). As the ship moved away from the banks, values of beam attenuation and relative CDOM fluorescence all decreased. Boss and Zaneveld (2003) found that bank regions, particularly reefs and seagrass beds, are sources of colored dissolved material, which is consistent with our findings.

The absorption properties of the study area are dominated by dissolved material as seen in the ratios of dissolved absorption to particulate absorption (\(a_d(440)/a_p(440)\)) (Table 1). Values of this ratio range from 1.4 to more than 4 on the banks, whereas in Exuma Sound the range was from 0.76 to around 2. These values are much higher...
Appendix 1: Previously published material (Continued)

greater than ranges reported in a Morel case 1 environment like the Gulf of Mexico, which are 0.3 to 0.7 (Walsh et al. 1992). Only in the clearest offshore waters of Exuma Sound could case 1 waters be found.

Time-series data collected just to the north of LSI in a tidally flushed channel (Fig. 1) show tidal fluctuations of water depth, temperature, salinity, density, and CDOM absorption (Fig. 4). As water depth increases on the flood tide, salinity and CDOM absorption decrease. On the ebb tide, as bank water is pushed into the sound, salinity and CDOM absorption levels in the tidal channel increase. Data from this time-series are consistent with our data, suggesting that water from the banks is rich in CDOM and relatively saline when compared with water from Exuma Sound.

Warmer daytime temperatures created on the banks by solar heating were seen during the ebb tide at around 4:00 p.m. on 20 May (Fig. 4). On the following ebb tide at around 6:00 a.m., however, no temperature increase is seen, consistent with the lack of heating during nighttime hours. On afternoon ebb tides, warmer temperatures associated with elevated salinities can create water that is less dense and likely to remain at the surface, whereas morning ebb tides, with low temperatures and elevated salinities, create dense water that is likely to sink as it moves away from the banks.

Table 1 Comparison of surface measurements of $a_g(440)$, $a_p(440)$, salinity, and the ratio $a_g(440)/a_p(440)$ at locations on and off the Bahamas Banks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_g(440)$</td>
<td>Banks</td>
<td>0.0429</td>
<td>0.0742</td>
<td>0.0586</td>
</tr>
<tr>
<td></td>
<td>Offshore</td>
<td>0.0141</td>
<td>0.0615</td>
<td>0.0302</td>
</tr>
<tr>
<td>$a_p(440)$</td>
<td>Banks</td>
<td>0.0064</td>
<td>0.018</td>
<td>0.0137</td>
</tr>
<tr>
<td></td>
<td>Offshore</td>
<td>0.0031</td>
<td>0.0182</td>
<td>0.0073</td>
</tr>
<tr>
<td>Salinity</td>
<td>Banks</td>
<td>37.01</td>
<td>37.6</td>
<td>37.18</td>
</tr>
<tr>
<td></td>
<td>Offshore</td>
<td>36.78</td>
<td>37.19</td>
<td>37.04</td>
</tr>
<tr>
<td>$a_g(440)/a_p(440)$</td>
<td>Banks</td>
<td>1.406</td>
<td>4.122</td>
<td>2.212</td>
</tr>
<tr>
<td></td>
<td>Offshore</td>
<td>0.758</td>
<td>1.990</td>
<td>1.231</td>
</tr>
</tbody>
</table>

Fig. 2 Relationship between salinity and CDOM absorption for both bank and sound locations during CoBOP 1999 and 2000. Boss and Zaneveld (2003) data were collected inshore near corals, sand, and grass beds during CoBOP 2000.

Fig. 3 Transect measurements made while underway from the Bahamas Banks into Exuma Sound. Beam attenuation at 488 (c488), 532 (c532), and 660 nm (c660) as well as CDOM fluorescence all decreased as the ship moved east, away from the banks.

Fig. 4 Time-series data collected during CoBOP 2000 from 20–21 May on the banks in a tidally flushed channel, courtesy of Boss and Zaneveld (2003). Solid line in each plot represents water depth (m). Dashed lines represent (A) salinity, (B) temperature, (C) sigma-t, and (D) CDOM absorption at 440 nm [a_g(440)].
Appendix 1: Previously published material (Continued)

For example, water from the morning ebb tide in Fig. 4C, with a sigma-t value of around 24.95 kg/m$^3$, has an ambient depth in Exuma Sound of around 40 m (Fig. 5C), whereas less dense water from the ebb tide the following afternoon (sigma-t $\approx$24.5) has an ambient depth near the surface (Fig. 5C). Because plumes have been found to entrain ambient sound water as they cascade over the shelf break (Hickey et al. 2000), this dense water from the morning ebb tide would reach a depth somewhat less than 40 m. On the next ebb tide on the afternoon of 21 May, however, water forced into the sound would remain at the surface.

A recent study of this region found that as these plumes leave the banks and cascade over the narrow shelf, they entrain ambient mixed-layer water of Exuma Sound and descend to the base of the mixed layer, where they can subsequently spread along isopycnals tens of kilometers into the sound (Hickey et al. 2000). Observed plume depths in November averaged 75 m, whereas the June plumes were observed at shallower depths (~45 m), consistent with shallower mixed-layer depths observed during the summer months. Subsurface salinity maxima were often associated with minima in percent light transmission, indicating a shallow-water, sedimented origin of plume water (Hickey et al. 2000).

Vertical profiles of temperature, salinity, sigma-t, and $a_g(440)$ collected during CoBOP 1999 are shown in Fig. 5. In Fig. 5D, the variability in $a_g(440)$ measurements of surface waters is high. CDOM absorption typically reaches a minima at the bottom of the mixed layer and then increases with depth. Mixed-layer depths of around 20 m down to 45 m are consistent with summertime salinity maxima found by Hickey et al. (2000) in Exuma Sound. The fact that these surface plumes involve not only increased temperature and salinity, but also $a_g(440)$, points to a saline, CDOM-rich origin, such as the shallow banks.

The role that wind forcing plays in the exchange of water between the banks and the deep basins can be examined here using depth profiles collected during CoBOP 1999 in Exuma Sound before and after a wind event (Fig. 6). During the wind event, wind speeds increased from approximately 4 m/s to around 6 m/s between 30 May and 3 June, and wind direction changed from around 50° (NE winds) to around 100° (ESE winds), impacting on a SE–NW-trending coastline. Figure 6 shows $a_g(440)$ vs. sigma-t before (24 May) and after (3 June) the wind event. Prior to the wind event, onshore NE winds suppressed offshore flow of water from the banks, and a sigma-t value of around 24.5 kg/m$^3$ represents a minima in $a_g(440)$. After the wind event, a similar sigma-t value represents a maximum in $a_g(440)$. This suggests that ESE winds forced CDOM-rich water from the banks and seagrass beds into Exuma Sound. High CDOM absorption was found with sigma-t values as high as 24.6 kg/m$^3$ on 6 June 1999, consistent with an ambient depth of about 25 m.

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Fig. 5 Profiles of A salinity, B temperature, C sigma-t, and D $a_g(440)$ vs. depth for 3 sampling days during the CoBOP 1999 experiment.

Fig. 6 Plots of $a_g(440)$ vs. sigma-t for all depths from two different profiles. The dotted profile was sampled prior to a wind event, whereas the solid profile was sampled after winds increased from 4 to 6 m/s and changed from NE to ESE. Both sites are offshore in Exuma Sound.
Figure 7 shows SeaWiFS images from 1999, covering Exuma Sound and TOTO, processed using the MODIS algorithm (Carder et al. 1999) to derive $a_g(400)$ values. To allow comparison to Table 1, values of $a_g(400)$ can be divided by 1.4 to estimate the $a_g$ value at 440 nm. This is because the spectral absorption of CDOM can be fit to the form $a_g(k) = A e^{-S(k-400)}$ (Roesler et al. 1989), where $S = 0.012$ is the spectral slope measured in Exuma Sound near LSI. Throughout the year, overall $a_g(400)$ levels in TOTO are roughly double those in Exuma Sound. Levels of $a_g(400)$ in both of these deep basins are significantly elevated compared to levels in the eastern edge of the Atlantic Ocean (NE portion of each image). The wintertime image (Fig. 7A) shows uniform $a_g(400)$ levels in TOTO and Exuma Sound. During the spring, summer, and fall, plumes rich in CDOM can be observed along the margins of both deep basins. In particular, the northern portion of Exuma Sound, which has no islands to contain water on the banks, has visible plumes in all but the wintertime image. The image from 26 May (Fig. 7D), collected during the CoBOP 1999 experiment, shows a distinct plume extending offshore from just south of LSI. Once in the sound, the plume is seen moving in a northwesterly direction, which is consistent with observed surface currents in Exuma Sound (Colin 1995).

SeaWiFS data processed using the Ocean Color 4 (OC4) algorithm (O’Reilly et al. 1998) to derive chlorophyll concentrations produced erroneously high estimates. When the image from 26 May 1999 (Fig. 7D), collected during CoBOP 1999, was processed with the SeaWiFS OC4 chlorophyll algorithm, chlorophyll estimates in the plume seen extending off the banks near LSI in Fig. 7D were about 0.17 mg/m$^3$. Using the Carder MODIS algorithm instead, produced chlorophyll estimates of around 0.11 mg/m$^3$. This value is much closer to the value of 0.08 mg/m$^3$ measured in the sound at the same site on the day of the image. Satellite-derived estimates of CDOM absorption...
in the same plume were on the order of 0.025 m\(^{-1}\) at 440 nm, which compare well with the measured value of 0.03 m\(^{-1}\) at 440 nm. By applying the Carder MODIS algorithm to SeaWiFS data, CDOM absorption is separated from phytoplankton absorption using the spectral differences between these components, providing chlorophyll estimates not contaminated by CDOM absorption.

One potential ecological impact of CDOM transport between the Bahamas Banks and the surrounding deep basins is on coral reefs that lie along the margin between the two regimes. Coral reef bleaching, the temporary or permanent loss of endosymbiotic algae (zooxanthellae) and/or their photosynthetic pigments, has been linked to elevated sea water temperatures as well as UV radiation (Glynn 1996). Coral reefs are present throughout the Exuma chain, consisting mainly of fringing reefs, located along the eastern margin of the Exuma chain, and channel reefs that are located in tidal channels between the banks and Exuma Sound (Chiappone et al. 1997). Coral reef bleaching has been documented near LSI as part of a widespread bleaching event in the Western Atlantic during the last half of 1987, and prolonged contact with warm, saline plumes originating on the banks and flowing out into Exuma Sound was hypothesized to be the cause (Lang et al. 1988). In addition, scleractinian corals in the area were found to be disproportionately affected on their upward-facing surfaces, indicating that exposure to solar radiation may have played a role in the onset of bleaching (Lang et al. 1988).

To estimate the impact that transport of CDOM over coral reefs might have on the underwater light field, Hydrolight (Mobley 1994) simulations were carried out to estimate the total absorption budget for the region and the spectral diffuse attenuation coefficient for downwelling light \(K_d(z)\). Hydrolight-derived \(K_d\)'s were then extrapolated to 300 nm using the slope of the CDOM absorption spectrum. Downwelling solar irradiance was measured on land during CoBOP 1999 and 2000 experiments. The influence of bottom reflectance was included in irradiance estimates by assuming a coral-sand bottom; however, bottom reflectance had a negligible effect on downwelling irradiance.

Hydrolight simulations of the water column absorption budget during ebb tide (bank water) are given in Fig. 8. In the UV and blue regions of the spectrum, total absorption is dominated by CDOM. Hydrolight-simulated absorption budget for Exuma Sound. In the ultraviolet and blue regions of the spectrum, total absorption is dominated by CDOM. Simulations were approximate mean values for bank and sound water determined experimentally during the CoBOP 1999 and 2000 experiments. The influence of bottom reflectance was included in irradiance estimates by assuming a coral-sand bottom; however, bottom reflectance had a negligible effect on downwelling irradiance.

For the ebb-tide case, when bank water flows into Exuma Sound, bank water conditions were used. Sound water conditions were used to simulate the flood-tide case when sound water extends onto the bank. Input parameters for the Hydrolight simulations for ebb- and flood-tide cases are given in Table 2. The contributions of minerals, CDOM fluorescence, chlorophyll fluorescence, and Raman scattering were not included as part of the simulations. Values of \(a_g\) and [Chl] used in Table 2 Input parameters for Hydrolight simulations

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Ebb tide case (bank water)</th>
<th>Flood tide case (sound water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDOM absorption:</td>
<td>(a_g/(440\text{ nm}))</td>
<td>0.06 m(^{-1})</td>
</tr>
<tr>
<td>Chlorophyll concentration:</td>
<td>[Chl]</td>
<td>0.12 mg m(^{-3})</td>
</tr>
<tr>
<td>Pure water absorption</td>
<td>(K_d)</td>
<td>(Pope\ and\ Fry (1997))</td>
</tr>
<tr>
<td>CDOM spectral slope</td>
<td>0.012</td>
<td>0.009</td>
</tr>
<tr>
<td>Solar zenith angle</td>
<td>3.0°</td>
<td>3.0°</td>
</tr>
<tr>
<td>Wind speed</td>
<td>1 m/s</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Cloud %</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Backscatter fraction</td>
<td>0.015</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Fig. 8 Hydrolight-simulated absorption budget for Exuma Sound. In the ultraviolet and blue regions of the spectrum, total absorption is dominated by CDOM.
Appendix 1: Previously published material (Continued)

spectral response function developed by Setlow to assess which wavelengths of UVR cause the most damage to DNA (inset, Fig. 10) (Setlow 1974). Dose-rate estimates of harmful UVR under flood tide conditions at a depth of 5 m reach a maximum of around $3 \times 10^{-4}$ (relative response) at 304 nm (Fig. 10). Under ebb-tide conditions, with increased CDOM absorption, the dose rate at 304 nm is approximately one-fourth of the flood-tide estimate. These estimates for the Bahamas are much higher than maximum dose rates estimated in the Florida Keys ($<10^{-5}$; Dunne and Brown 1996). In the Florida Keys study, dose rate estimates at 5 m from this study are around 50% of surface values, whereas during ebb tide, the value drops to around 12% (Table 3). These data indicate that waters surrounding LSI are very clear, and corals in this region can be exposed to high levels of DNA-damaging radiation if they grow as shallow as 5 m. Relative dose-rate levels at 304 nm as a percentage of the surface dose rate at three different depths (5, 10, 15 m) under ebb and flood tide conditions are given in Table 3 for comparison.

Plumes flowing off the banks and into Exuma Sound are important to reefs not only as warm, saline water sources, which may expose corals to temperature and salinity extremes, but also because the associated dissolved material has the ability to protect corals from UV and visible radiation.

Conclusions

The optical properties of the environment surrounding Lee Stocking Island are dominated by dissolved substances. Boss and Zaneveld (2003) showed that, on the banks, absorption due to CDOM was higher closer to the bottom, indicating seagrass beds, reefs, and benthic organisms living in and on bank sediments are a source of CDOM. Coastal depth profiles exhibiting surface maxima in salinity, and CDOM absorption suggest that water from the Bahamas Banks flows offshore into Exuma Sound. Density fluctuations on the banks associated with solar heating and evaporation cycles will have a large impact on whether plumes remain at the surface or sink to depth. CDOM contained in dense plumes that sink to depth will be exposed to less light at depth with less chance of being photo-oxidized. Both the CDOM-rich, saline plumes found at depth and those that remain on the surface observed in SeaWiFS imagery are hypothesized to be the result of a Bahamas Banks source with shallow-water evaporation, followed by tidal and wind advection into deeper water. Water exported at the end of a solar heating cycle can be buoyant enough to remain at the surface offshore, whereas water exported at the end of a nocturnal cooling period likely dominates the plumes found at depth. From SeaWiFS imagery, we can observe that plumes of CDOM-rich water produced on the Bahamas banks flow out into both TOTO and Exuma Sound at various times throughout the year.

Table 3 Percentage of surface dose rate at different depths for ebb and flood tide cases

<table>
<thead>
<tr>
<th>Tidal stage</th>
<th>Ebb</th>
<th>Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>% of surface dose rate</td>
<td>12.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Because wind forcing plays a large role in the transport of material from the banks into deep basins, plume development is variable. CDOM transported from the banks, over coral reefs, and into deep basins affects the underwater light field by absorbing UVR and cutting the level of DNA-damaging radiation to which the reefs are exposed. Future work in this area will include further studies of seasonal and annual variations in the development of CDOM-rich plumes in the Bahamas.

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References


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