Environmental variability in the Florida Keys: Impacts on coral reef health

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Environmental Variability In The Florida Keys: Impacts On Coral Reef Health

by

Inia M. Soto

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
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University of South Florida

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This Master of Science thesis is dedicated to my family and friends for supporting me throughout this journey, but particularly to my parents, Gloria E. Ramos and Rafael A. Soto, for giving me the support, love, and encouragement to achieve my goals.
Note to the reader: The original document contains color which is necessary to fully understand some figures. The original manuscript is on file with the USF library in Tampa, FL.
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Environmental Variability in the Florida Keys: Impacts on Coral Reef Health

Inia M. Soto

ABSTRACT

I examined the hypothesis that high variability in Sea Surface Temperature (SST) and ocean color are associated with higher coral cover and slower rates of decline of coral cover within the Florida Keys National Marine Sanctuary (FKNMS). Synoptic SST time series maps, covering the period 1994-2005, were constructed for the FKNMS with data collected using the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite sensors. The SST data were compared with coral cover time series assessments at 36 sites conducted by the Coral Reef and Evaluation Monitoring Program (CREMP; 1996-2005), sponsored by the Environmental Protection Agency and the State of Florida. Out of the 36 stations, Smith Shoals routinely experienced very different and extreme environmental conditions relative to the rest of the stations, including extreme salinity, suspended sediments, and “black water” events that led to the death of coral reef organisms such as in 2002. Among the other 35 stations, sites that experienced moderately higher SST variability (mean variance >6) relative to other sites showed a trend toward higher percentage coral cover ($r=0.62$, $p=6.33\times10^{-5}$, $N=35$) and relatively slower rates of decline ($r=0.41$, $p=0.02$, $N=35$) over the 12-year study period. The results suggest that coral reefs sites that are continuously exposed to high but not extreme variability in temperature may develop resilience against episodes of extreme cold or elevated SST.

Variability of suspended sediments and water clarity were estimated using satellite-derived, normalized water-leaving radiance products. Ocean color data were obtained from the Sea-viewing Wide-Field-of View Sensor (SeaWiFS) from 1998 to 2005. Normalized water-leaving radiance at 443 ($L_{wn}^{443}$) was used as a proxy to examine variability in water clarity, and normalized water-leaving radiance at 670 ($L_{wn}^{670}$)
670) was used as a proxy to study variability in suspended sediments. A weak relationship was identified between variability of $L_{wn}443$ and $L_{wn}670$ and coral cover as estimated by CREMP assessments in 2005 ($r=0.43$, $p = 0.01$, $N=35$ and $r = 0.47$, $p = 0.005$, $N=35$, respectively). There was a weak relationship between coral cover change and $L_{wn}670$ from 1988 to 2005 ($r = 0.46$, $p = 0.05$, $N=35$), but there no relationship was observed between variability of $L_{wn}443$ and change in coral cover ($r =0.27$, $p =0.11$, $N=35$). Further research is required to understand the origin, concentration and composition of dissolved or suspended materials that change the turbidity of waters around reefs of the FKNMS, and whether these changes can be adequately interpreted by examining concurrent satellite imagery. Ultimately, such remote sensing and field research is required to understand how water quality affects the health of coral reefs, and how coral ecosystems adapt to environmental variability.

1.1. Introduction

Coral reef ecosystems provide essential habitat, food and shelter for a variety of marine organisms. They also help protect coastlines from storm damage, erosion, and flooding by reducing wave action (Hoegh-Guldberg 1999). Coral reefs yield substantial support for the global economy in terms of food, recreation and jobs (Pandolfi et al. 2005). In the Florida Keys, coral reef environments support approximately $490 million a year in sales and 8,000 jobs (Johns et al. 2001). Despite their socio-economic importance to our coasts and communities, every coral reef ecosystem under U.S. jurisdiction has suffered from some degree of disturbance (Turgeon et al. 2002). Coral bleaching has been one of the prime causes of declines in the coral cover of the Florida Keys (Causey et al. 2002). Some reefs off Florida, Puerto Rico, the U.S. Virgin Islands, the Main Hawaiian Islands, and Guam have been degraded by multiple environmental and human-induced stresses due to their close proximity to coastal population centers (Turgeon et al. 2002). Indeed, coral reefs worldwide are a threatened ecosystem (Dustan 1999).

Many natural forces such as hurricanes, ocean temperature fluctuations, and sea level change have impacted global coral reefs for millions of years. Human stressors have rapidly increased in the last 50 years with negative effects on coral reef health. For example, increased sedimentation will smother corals, increased nutrients and decreasing herbivore populations will result in algal overgrowth, sustained elevated temperatures promote bleaching, and some coral diseases appear correlated to coastal development (Dustan 1999). The combination of natural and human stressors may hasten the degradation of local reef ecosystems.
This study analyzes the possible effect of Sea Surface Temperature (SST) variability as a factor affecting the resilience of coral reef communities in the Florida Keys National Marine Sanctuary (FKNMS; Fig. 1.1). The primary hypothesis is that higher coral cover and less change in cover occurs at locations with higher temporal SST variability. The approach was to examine SST variability in and near various geomorphological classes in the FKNMS in a synoptic fashion, using time series of SST estimated with the NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite sensors. Coral reef cover and change data were obtained from the Coral Reef and Evaluation Monitoring Program (CREMP) sponsored by the Environmental Protection Agency and the State of Florida.

1.2. Methods

1.2.1. Coral Reef Cover and Change Data

The FKNMS covers 9950 km$^2$ (Causey et al. 2002) of various geomorphological classes including nearshore and offshore patch reefs, seagrass beds, back reefs and reef flats, hard-bottom communities, bank or transitional reefs, deep reefs, outlier reefs, and sand/soft bottom areas (Keller et al. 2003). The CREMP is a large temporal and spatial scale coral reef monitoring program that started sampling in 1996 with 40 sites throughout the Florida Keys. Three stations in the Dry Tortugas were added in 1999. Porter et al. (2002) provides details of the CREMP program methodology and procedures. Field sampling consists of species inventories and video transects at each site. The 43 sampling sites include 7 hardbottom, 11 patch, 12 offshore shallow, and 13 offshore deep reef sites. Hardbottom sites were not included in this study due to the extremely low abundance of stony coral. For the remaining 36 stations (Fig. 1.1), the percent of stony coral present in 2005 was considered, as well as the coral cover change (the difference of stony coral cover) between 1996 and 2005. For the three Dry Tortugas stations established in 1999, the coral cover change was estimated only from 1999 to 2005. The difference was normalized by dividing by the percent of stony coral observed in 1996 for most sites, or 1999 for the Dry Tortugas. Annual coral cover change (e.g.,
1997 to 1998) was also calculated, and the difference was normalized by dividing by the coral cover of the previous year. Smith Shoal was considered a site that experiences very different conditions compared to all other CREMP sites. Here I examine the same sites including and excluding Smith Shoal.

Figure 1.1: CREMP stations throughout the Florida Keys. (Top panel) offshore shallow reefs; (middle panel) patch reefs; (bottom panel) offshore deep reefs
1.2.2. Assessing Environmental Variability

Full resolution (1 km$^2$) infrared (IR) data were derived from the AVHRR sensors on the NOAA polar orbiting environmental satellites. The images were collected using a High Resolution Picture Transmission (HRPT) antenna located at the University of South Florida, in St. Petersburg, FL. SST was calculated from the satellite infrared observations using the multi-channel sea surface temperature (MCSST) algorithm developed by McClain et al. (1983). All SST images from 1994 to 2005 were collected and mapped to a cylindrical equidistant projection. A weekly climatology of SST was derived and used to compare each individual image with the corresponding weekly climatology file. Erroneous SST estimates due to cloud contamination were identified by comparing individual daily image pixels with weekly climatologies, and values where the absolute difference was higher than four degrees Fahrenheit were discarded from further treatment. Additional treatment included computing a three-day median filter where SST values differing by at least 2 degrees from the calculated median value at each pixel were discarded. New weekly climatologies and mean weekly composites (Fig. 1.2 shows an example of two weekly means images: winter 1998 and summer 1998) for each year were recreated from the filtered images.

Mean variance was used as a measure of variability of SST. For each station, the variance in the weekly averaged temperatures was calculated for the 12-year period. Annual variance was calculated from mean weekly SST for every year and compared to the annual change in stony coral. This resulted in a total of 36 values per year (one for each station) or total of 432 values for twelve years. Regression and correlation coefficient analyses were used to examine relationships between variance in SST, coral cover, and coral cover change. A randomization test and Monte Carlo analysis were used to determine significant differences among variances of SST per year. The test was based on 36 random variance values out of the total 432 and calculating the variance. This process was repeated 10,000 times to determine the probability of obtaining the same variance for each year.

1.3. Results

The CREMP results show that only five out of the 36 stations showed over 15% stony coral cover in 2005 (Western Washer Woman, Western Head, Admiral, Jaap Reef, and Dustan Rocks). The maximum coral cover was 24% (Western Head). While average stony coral cover for all sites was an average of 11.9% in 1996, by 2004 this had declined to 6.6% (Beaver et al. 2004). The sites showing greater coral cover in 2005 also showed slightly higher SST variability in surrounding waters (Fig. 1.3, $r = 0.62$, $p = 6.33 \times 10^{-5}$, $N=35$). Patch reefs experienced higher variability in temperature and featured higher percentages (>15%) of stony coral cover than offshore deep and shallow coral reefs, where the lowest coral cover and also the lowest SST variability were observed (Fig. 1.3).

Variability in SST did have a significant effect on the estimated overall rate of coral cover decline between 1996 and 2005 (Fig. 1.4, $r = 0.41$, $p = 0.02$, $N=35$). Individual sites with average or smaller SST variability (variance of ~6) appeared to show faster decline in coral cover (>0.8 loss) than areas with higher variability (variance >6.5). Patch
reefs showed the lowest rate of decline, followed by offshore deep reefs and offshore shallow reefs. The latter had the fastest rates of decline (Fig. 1.4).

Additional factors might also influence the observed decline rates. For example, Smith Shoal Reef showed the highest variability in temperature and relatively low abundance of coral (coral cover in 2005 = ~7%, Variability of sst = ~11.7). Smith Shoal is located to the north of the Florida Keys tract and is openly exposed to Florida Bay. It experiences more extreme fluctuations in sediment load, salinity, and anomalous conditions such as “black water” events (Hu et al. 2003). The 2002 “black water” event alone was associated with a reduction of nearly 68% of coral cover at Smith Shoal (Hu et al. 2003). This large (>60 km diameter) dark patch of water contained a diatom bloom and red-tide organisms, and it appears that the stagnation of the water for up to two months near Smith Shoal may have triggered the mortality of many organisms of the

Figure 1.3. Comparison between coral cover in 2005 and variability of SST from 1994 to 2005 (m = 0.04, b=-0.18, r=0.62, p = 6.33x10^{-5}, N=35). The dotted lines represent the 95% confidence intervals.
coral reef community. Most other CREMP sites suffered significant stony coral cover loss in 1998 as a result of a sustained warm event, but coral cover at Smith Shoal did not change that year.

Removing Smith Shoal from the ensemble of CREMP sites examined increases the correlation coefficient between coral cover and SST variance from 0.47 (figure not shown) to 0.62 (p=6.33x10^{-5}, N=35), and between coral cover change and SST variance from 0.27 (figure not shown) to 0.47 (p= 0.015, N=35). Coral at Smith Shoal may therefore be stressed and vulnerable to a variety of extreme stresses that mask any resiliency built by exposure to temperature variability.

Variability in ocean temperature can result from ENSO events, characteristics of a site (e.g., depth and water circulation), or simply latitude variation among the sites. Indeed, I detected significant interannual SST variability throughout the FKNMS. Mean

![Graph](image)

Figure 1.4. Comparison between coral cover change from 1996 to 2005 and variability of SST (estimated between 1994 to 2005) (m = 0.10, b=-1.06, r=0.41, p = 0.02, N=35). The dotted lines represent the 95% confidence intervals.
SST variability was higher in 1998 than in other years (mean of variance = 7.66; Fig. 1.5a). In 1998, the Pacific Ocean experienced an El Niño-Southern Oscillation event (ENSO), which may have led to above average temperatures in the FKNMS. Indeed, coral bleaching events were documented worldwide during 1998 (Wilkinson 1998). CREMP reported a significant decline in mean percent stony coral cover from 1997 to 1998 and from 1998 to 1999 (p-value of 0.03 or less for the Wilcoxon rank-sum test; Beaver et al. 2004). During 1996 and 2005, the variability in temperature was also high (mean of variance = 7.66 for 1996 and 7.33 for 2005). The probabilities of obtaining such high mean variances as observed in 1996, 1998, and 2005 was extremely low (less than 1%; Fig. 1.5a and 1.5b) per the Monte Carlo tests.

The rate of change in coral cover was higher from 1997 to 1998 and from 1998 to 1999 than in other years. During these years, the mean coral cover change for all the stations was -0.21 for 1997-1998 and -0.23 for 1998-1999, while the mean from all the years ranged from 0.013 to -0.08 depending on station.

1.4. Discussion

Temperature is not the only stressor influencing coral reefs in the region, as evidenced by the drastic mortality at Smith Shoal due to the 2002 “black water” event. Porter et al. (2001) reported an increase in coral diseases in the Florida Keys from 1996 to 1998. Poor water quality due to increased nutrient concentrations, large salinity fluctuations, and coral bleaching may be in part responsible for lowering the resistance of coral against diseases (Wells 1932; Cook et al. 1990; Coles and Jokiel 1992; Porter et al. 1999; Porter et al. 2001). Prolonged elevated ocean temperatures also accelerate the growth of pathogens (Acosta 2001; Alker et al. 2001). The actual cause of the coral reef decline at the CREMP sites is, unfortunately, beyond the scope of the study, and remains to be determined.

Results show that stony coral benthic cover in the Florida Keys between 1996 and 2005 was more stable in areas that experienced higher SST variability. Such areas seemed better prepared to resist abrupt changes in temperature. Therefore, in areas of higher SST variability that are sheltered from direct impact from other stressors such as
Figure 1.5. Analysis of annual SST variability from 1994 to 2005. a) Variance of the mean SST all coral reef sites per year. The error bars show the variance among the stations and they were centralized by the middle point. b) Randomization test and Monte Carlo analysis results. The histogram represents the frequency of obtaining the same variance values per year.
higher nutrient or sediment loads might be better suited for successful stony coral settlement, recruitment and long-term survival. This suggests an acclimation of the coral to cope with changes in temperature, including the more extreme changes associated with ENSO. Whether this acclimation also leads to resistance to diseases is not clear.

The "intermediate disturbance hypothesis" of Connell (1978) is a theory of ecology that seeks to explain how communities can acclimate to environmental disturbance. Similar concepts were proposed 25 years earlier by Hutchinson (1953). The hypothesis contends that without disturbances, communities would reach an equilibrium in which competitively superior species exclude others. However, a disturbance that kills or damages individuals will set back the process of competitive elimination and open new space that can be colonized by less competitive individuals (Colin et al. 1997). One fundamental assumption of the theory is that, if disturbance occurs frequently, then richness will decrease and species tolerant to change will become more abundant (Collins et al. 1995).

The extent of coral adaptation or response to thermal stress is still not clear. Indeed, the propensity of corals to bleach depends on the sensitivity of different symbionts hosted by the coral (Rowan et al. 1997; Hughes et al. 2003). Baker et al. (2004) showed that corals containing the unusual thermally-tolerant algal symbiont, Symbiodinium D, were more abundant on reefs after episodes of severe bleaching. Rowan (2004) also found Symbiodinium D to be more tolerant of higher temperatures (32ºC) than Symbiodinium C, and suggested that coral specimens of the genus Pocillopora hosting Symbiodinium D are less affected by periods of increased ocean temperature and are also found in warmer habitats.

Further research is needed to understand how temperature adaptation or sensitivity influences the distribution and survival of coral reef in the Florida Keys. Other factors like variations in bottom temperature, upwelling events, nutrient load and other water quality factors, UV radiation, harmful algal blooms, diseases, and even decreases in the pH of seawater due to ocean acidification also need to be considered when analyzing the origin of resilience in coral reefs. Understanding these factors, and whether particular reefs are exposed to a subset or all of them, will help understand how to manage anthropogenic factors, such as impacts due to coastal development, divers and fishers.
1.5. Conclusion

To understand how variability of SST can influence coral reef health, variability of SST from 1998 to 2005 was compared with coral cover in 2005 and coral cover changes in the Florida Keys. Coral cover was higher (>10%), and the percentage of coral cover lost was lower (<30%) in areas with higher variability of SST (mean variance >6). This result suggests that some coral species have acclimatized to the variability in temperature, increasing the resistance to abrupt changes in temperature. The results show that temperature variability plays an important role in the distribution, abundance, and survival of coral reefs. However, it is clear that other factors contribute to the health of coral reefs. Scientists are only beginning to understand the process of acclimatization and the role that disturbance factors like pollution, sedimentation, or others play in defining the distribution, resilience and ultimate survival of coral reef communities.
2. Chapter Two. Variability of Ocean Color in the Florida Keys: Impacts on Coral Reef Health

2.1. Introduction

Reef-building corals are generally considered to be limited to warm, clear and shallow waters (Kleypas et al. 1999). However, some coral reefs are found in turbid water and at depths that exceed 10 m (Yentsch et al. 2002). Indeed, many reefs exist in highly turbid and nutrient-rich coastal waters (Hughes et al. 1999). Light is also typically considered to be a limiting factor for coral reef growth, but many corals and their zooxanthellae exhibit versatility with respect to their ability to acclimatize to low or high light intensity (Hoegh-Guldberg 1999).

The reasons why some of the most luxuriant coral reef communities are found in areas with high sediment load or other factors that cause high turbidity is still unclear. Dustan (1999) suggested that some coral reefs develop in places where they are routinely affected by drastic changes, while others have evolved under more stable environmental conditions. The latter communities may not have the ability to adapt or “cope” when drastic environmental change occurs. On the other hand, Gilmour (1999) suggested that coral reefs affected by routine disturbance, such as those in areas with high sedimentation, tend to have lower diversity and are simply dominated by sediment-resistant species.

In the Florida Keys, there is growing evidence that a decline in water quality due to development of the coastal zone of Florida is threatening the health of coral reef communities (LaPointe et al. 1990; LaPointe & Clark 1992; LaPointe & Matzie 1996; Szmant & Forrester 1996; Porter et al. 1999). Concern about the health of the reef has led to attempts to improve water quality in the Florida Keys since the mid-1990’s. Specifically, the City of Key West upgraded wastewater treatment facilities, a new
treatment plant was developed in the City of Marathon, and all state waters in the Florida Keys were declared a non-discharge zone for boat-generated sewage (Krucynski 2005). However, wastewater discharge is not the only factor affecting the water quality in the Florida Keys. Other human activities [e.g., growing coastal population, rising tourist numbers, poor agriculture practices, construction, and others] near the coast (Burk and Maidens 2004) are also major contributors to the decline in water quality.

The quality of coastal marine water may be assessed in a practical manner by analyzing its color. Satellite remote sensing allows such assessments rapidly and repeatedly, over regional to synoptic scales (Palandro et al. 2004). Ocean color sensors measure the amount of light reflected from the surface of the ocean at specific wavebands (Gordon and Morel 1983). Satellite ocean color observations began in the late 1970s with the Coastal Zone Color Scanner (CZCS), which acquired data from 1978 to 1986. The CZCS helped understand the global distribution of phytoplankton, and defined the theoretical and practical bases for the next generation of ocean color sensors, including the Sea-viewing Wide-Field-of View Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectrometer (MODIS).

Coastal environments present a challenge for ocean color studies because the color does not depend only on phytoplankton concentration or optical constituents that covary with it (Morel and Prieur 1977; O’Reilly et al. 1998). Tidal currents, river discharge, and resuspension of bottom material from wave action and storms can also rapidly alter the optical properties of the water (Gould and Arnone 1997). Due to the range of environmental variables that can affect satellite-derived coastal water color measurements; it is difficult to conclusively and routinely identify which constituents affect the water-leaving radiance signal without an independent measure of at least some of the constituents at some locations in the image. Yet, several studies have used satellite ocean color data to assess the quality of coastal water, including estimating total suspended sediments (e.g. Stumpf and Pennock 1989; Hu et al. 2003; Palandro et al. 2004; Miller and McKee 2004).

In this study I examined the temporal and spatial variability of normalized water-leaving radiance at 443 nm and 670 nm ($L_{wn443}$ and $L_{wn670}$) as indices of variability in
water quality around the Coral Reef Evaluation and Monitoring Program (CREMP) sites in the Florida Keys National Marine Sanctuary (FKNMS). Water-leaving radiance is the upwelling radiance measured just above the surface (Mobley 1994). Normalized water-leaving radiance \( L_{wn} \) is the water-leaving radiance normalized to a single sun-viewing geometry, taking into account the solar zenith angle and the earth-sun distance (AU units) (Gordon and Clark 1981). The earth-sun distance accounts for the variability caused by the eccentricity of the earth about the sun, and the cosine of the solar zenith angle is used to reference the solar irradiance to a horizontal surface to the solar beam. \( L_{wn443} \) will be used as a proxy for water clarity (i.e., turbidity), and \( L_{wn670} \) as a proxy for suspended sediment load.

Mean variance in \( L_{wn443} \) and \( L_{wn670} \) from 1998 to 2005 was compared with coral reef cover and change data collected by the CREMP, sponsored by the Environmental Protection Agency and the State of Florida. The objective of this study is to determine if areas with higher coral cover and less change in coral cover over time are correlated to changes in the blue (443) or red (670) color reflectance caused by variability in sediment concentrations or other factors that may affect water clarity.

### 2.2. Methods

#### 2.2.1. Coral Reef Cover and Change Data

The methodology for the analysis of the coral reef and CREMP monitoring data is outlined in Chapter 1. Smith Shoal was considered a site that experiences very different conditions compared to all other CREMP sites. Here I examine the same sites including and excluding Smith Shoal.

#### 2.2.2. Assessing Environmental Variability

Full resolution (1 km\(^2\) / pixel at nadir) ocean color data were derived from the SeaWiFS. The images were collected using a High Resolution Picture Transmission
SeaWiFS has a swath width of 2,801 km, two day temporal resolution, and eight spectral bands (Hu et al. 2000). The ocean color products were derived with the SeaDAS software (Version 4) developed at National Aeronautics and Space Administration (NASA). The atmospheric correction was based on that used by Gordon and Wang (1994), Ding and Gordon (1995) and Siegel et al. (2000). Ocean color water-leaving radiance products from 1998 to 2005 were mapped to a cylindrical equidistant projection. Weekly mean composites of $L_{\text{wn}443}$ and $L_{\text{wn}670}$ were calculated for the 7-year period (Fig. 2.1 shows an example). Data were filtered for negative and zero values to remove $L_{\text{wn}}$ values that were erroneous due to atmospheric correction issues (Hu et al. 2000) or cloud cover.

For each CREMP station, the mean variance of the weekly averaged $L_{\text{wn}443}$ and $L_{\text{wn}670}$ was calculated for each year. The variability of the ocean color data was compared to stony coral cover and coral cover change using linear regressions and correlation coefficients. This generated a total of 36 values (one per station, including Smith Shoal) per year, for a total of 288 statistics over eight years. A randomization test and Monte Carlo analysis were used to determine whether there were significant differences among the annual variances of water clarity and suspended sediments. The randomization test extracts 36 random variance values out of the total 288 and calculates the variance. This process was repeated 10,000 times to determine the probability of obtaining the same variance for each year.

The mean variance of the $L_{\text{wn}443}$ and $L_{\text{wn}670}$ weekly averages were compared to depth to determine whether bottom reflectance had an influence on the variability of water-leaving radiance. Depth was obtained from a bathymetry created by Palandro (2006) from a combination of datasets (Benthic Habitats of the Florida Keys or BHFK from NOAA and the Florida Fish and Wildlife Conservation Commission or FWCC, NOAA’s Geophysical Data System or GEODAS, and the FWCC bathymetric dataset by Chris Anderson based on Landsat imagery) and an interpolation of Landsat imagery. The resulting bathymetric map provides complete coverage of the Florida Keys Reef Tract, with a vertical resolution of 1 m between 2 and 20 m, and a horizontal resolution of 30 m.
Figure 2.1. Examples of SeaWiFS weekly mean water-leaving radiance. Weekly mean of the second week of June 1998. a) $L_{\text{wn}443}$. b) $L_{\text{wn}670}$.
2.3. Results

2.3.1. Normalized water-leaving radiance at 443 nm

A weak relationship was observed between variability of $L_{wn443}$ and coral cover in 2005 alone ($r=0.43$, $p = 0.01$, $N=35$, Fig. 2.2). However, no relationship was found between variability of $L_{wn443}$ and change in coral cover from 1988 to 2005 ($r =0.27$, $p = 0.11$, $N=35$, Fig. 2.3). There was no significant change in these trends when Smith Shoal was excluded from the analysis.

![Graph showing comparison between stony coral cover in 2005 and variability of $L_{wn443}$ from 1998 to 2005 (m = 0.20, b=-0.02, r=0.43, p = 0.01, N=35). The dotted lines represent the 95% confidence intervals.](image)

Figure 2.2. Comparison between stony coral cover in 2005 and variability of $L_{wn443}$ from 1998 to 2005 ($m = 0.20$, $b=-0.02$, $r=0.43$, $p = 0.01$, $N=35$). The dotted lines represent the 95% confidence intervals.

Patch reef sites showed higher variability of $L_{wn443}$ (variance values ranged from 0.3 to 0.7) compared to offshore deep and offshore shallow sites (variance values ranged
from 0.1 to 0.6). Offshore deep and offshore shallow reefs showed the lowest percentages of coral cover (less than 5%), however not all of them showed low variability of \( L_{wn443} \). The weak positive relationship between mean \( L_{wn443} \) and coral cover in 2005 was driven by patch reefs.

Annual variability of \( L_{wn443} \) (Fig. 2.4a) from 1999 to 2005 ranged from ~0.3 to 0.4 (variance), much lower than the mean variability in 1998 (0.56). The Monte Carlo test identified the probability of obtaining mean variance as high as observed in 1998 to be extremely low (less than 1%; Fig. 2.4a and 2.4b).

Figure 2.3. Comparison between change in coral cover between 1996 and 2005 and overall variability of \( L_{wn443} \) from 1998 to 2005 (m = 0.45, b=-0.64, r=0.27, p = 0.11, N=35). The dotted lines represent the 95% confidence intervals.
Figure 2.4. Analysis of annual \( L_{\text{ww}443} \) variability from 1998 to 2005 a) Variance of the mean \( L_{\text{ww}443} \) for all coral reefs sites per year. The error bars show the variance among the stations and they were centralized by the middle point. b) Randomization test and Monte Carlo analysis results. The histogram represents the frequency of obtaining the same variance values per year.
2.3.2. Normalized water-leaving radiance at 670 nm

For every CREMP station, the mean variance (variability) of the weekly average \( L_{wn}670 \) from 1998 to 2005 was calculated and compared with the coral cover in 2005 and the coral cover change from 1998 to 2005 (Figures 2.5 and 2.6). When including Smith Shoal, a weak relationship was present between the variability of \( L_{wn}670 \) and coral cover in 2005 \( (r = 0.37, p = 0.03, N=35) \). This indicated a weak trend between higher variability and higher coral cover. Indeed, some patch reefs like Admiral, Black Coral and Jaap have less than 20% coral cover, but the first two have a mean \( L_{wn}670 \) variance of \( \sim 0.04 \) and Jaap reef has a mean variance of 0.28. Smith Shoal showed the highest variability of \( L_{wn}670 \) (0.38). When Smith Shoal was removed from the analysis, the relationship

![Figure 2.5. Comparison between stony coral cover in 2005 and variability of \( L_{wn}670 \) from 1998 to 2005 (\( m = 0.60, b=0.01, r=0.47, p = 0.01, N=35 \); i.e. excluding Smith Shoal). The dotted lines represent the 95% confidence intervals.](image-url)
between L<sub>wn</sub>670 variability and coral cover increased (r = 0.47, p = 0.01, N=35; Fig. 2.5). It is reasonable to expect higher variability in Smith Shoal because it is located near the mouth of Florida Bay and is constantly exposed to sediment flux from the Bay. A weak relationship was also present between the mean variance of L<sub>wn</sub>670 and change in coral cover from 1998 to 2005 (r=0.33, p = 0.05, N=36). This relationship was stronger when Smith Shoal was removed from the analysis (r = 0.46, p = 0.05, N=35; Fig. 2.6).

![Graph showing comparison between change in coral cover and overall variability of L<sub>wn</sub>670 from 1998 to 2005](image)

**Figure 2.6.** Comparison between change in coral cover between 1996 and 2005, and overall variability of L<sub>wn</sub> 670 from 1998 to 2005 (m = 1.77, b=-0.61, r=0.46, p = 0.01, N=35). The dotted lines represent the 95% confidence intervals.
Figure 2.7. Analysis of annual L\text{wn}670 variability from 1998 to 2005 a) Variance of the mean L\text{wn}670 for all coral reef sites per year. Error bars show variance among stations and they were centralized by the middle point. b) Randomization test and Monte Carlo analysis results. The histogram represents the frequency of obtaining the same variance values per year.
While the range of the annual variability in L
\textsubscript{443} was less than half of that observed in L
\textsubscript{670}, both showed some similarity in their temporal patterns (Fig. 2.7a). In 1998, the mean L
\textsubscript{670} variability was higher (0.2) than from 1999 to 2004 (mean variance ranged from 0 to 0.15). The probabilities of obtaining such high mean variance as observed in 1998 was extremely low (less than 1%; Fig. 2.7a and 2.7b) per Monte Carlo test. However, for both L
\textsubscript{443} and L
\textsubscript{670}, the error bars in the mean annual variance were large, showing that these parameters fluctuated substantially among sites. There was no relationship between bottom depth and the mean or the mean variance of L
\textsubscript{443} or L
\textsubscript{670} (the correlation coefficient varied from -0.25 to 0.11; figures not shown). Also, coral cover in 2005 and coral cover change were not correlated with depth (r = -0.24, N=36 and r = -0.14, N=36 respectively; figures not shown).

2.4. Discussion

During 1996 to 1997, corals near population centers in the Florida Keys seem to have developed elevated percentages of diseases, and by 1998 no area was without infection (Porter et al. 2001). Between 1998 and 1999, a significant decline in coral cover in the Florida Keys was observed (Beaver et al. 2004). My results may help explain some of the spatial patterns observed in these changes.

I found an association between variability in both temperature and water quality and areas of higher coral cover. However, years during which extreme environmental variability was caused by several events, including El Niño-Southern Oscillation (ENSO) events and hurricanes, experienced higher than normal decline in coral cover, regardless of initial coral cover. This suggests that there may be a range of acceptable environmental variation or combination of stressors (e.g. high temperature and high turbidity) within which coral reef communities are resilient to stress, but such resilience is diminished under either more stable or more extreme conditions.

This study found no significant relationship between blue light (L
\textsubscript{443}) variability and coral cover change in the FKNMS between 1998 and 2005. However, there was a very weak indication that coral cover as estimated in 2005 was higher at
CREMP stations with higher variability of $L_{443}$ and $L_{670}$. Additionally, a slightly lower decline in coral cover was found in areas with higher variability of $L_{670}$.

The variability of either $L_{443}$ or $L_{670}$ is difficult to interpret. In an attempt to determine which factor (phytoplankton, CDOM, or turbidity from suspended sediments) caused observed variability, I compared the means of $L_{443}$ and 670 with the variability of $L_{443}$ and 670 by using regression analysis. As with many natural variables, significant correlation was present between mean $L_{443}$ and 670 and their respective variability ($r=0.75$, $N=36$ and $r=0.79$, $N=36$, figures not shown). The variability for $L_{443}$ is larger during turbidity or sediment resuspension events.

Low values of $L_{443}$ in coastal water suggest high light absorption by either phytoplankton or colored dissolved organic matter (CDOM), while high values suggest high turbidity (Hu et al. 2003). CDOM absorbs very little in the red wavelengths but its absorption in the blue wavelengths can be significant. Chlorophyll and other phytoplankton pigments absorb light in the blue as well as in the red (Mobley 1994). In contrast, the irradiance measured above the water surface typically increases with the concentration of suspended inorganic sediments at wavelengths from 450 to 900 nm in fresh waters (Ritchie et al. 1976; Munday and Alföldi 1979).

Sediments play an important role in the survival of coral reefs. Large fluxes of sediment material can smother coral tissue; impeding gas exchange, reducing light available for photosynthesis, and increasing energy spent cleaning and/or removing the sediments from the surface of the coral (Dustan 1999). Conversely, severe bleaching events have been attributed to high levels of solar irradiance (Fisk and Done 1985; Harriot 1985). Our results show slightly higher coral cover in areas with higher variability in $L_{443}$ and 670. It would appear that some corals survive and perhaps adapt better in these variable conditions. A proposed benefit of this adaptation is reduced severity of future bleaching events due to reduced exposure to high light radiation.

Another important result was that the variability of $L_{443}$ was twice as high as the variability of $L_{670}$ (0.0 to 0.8 and 0.0 to 0.4, respectively). Clearly, the absorption of red light by water is much stronger than that of blue light (Kirk 1985), and naturally more blue light is reflected by the ocean. $L_{443}$ variability is also higher than that of
L_{wn}670, in part simply because the absolute values of L_{wn}443 are higher. Second, this coastal environment is frequently influenced by fluxes of water from Florida Bay. I therefore speculate that variation in CDOM and phytoplankton concentration largely contributed to the observed variability in blue light.

In 1998, annual mean variability of L_{wn}443 and L_{wn}670 was significantly higher than in the others years studied. Two episodes led to this higher variability. The first was likely the ENSO event of the 1997-1998 with associated increased winter storm frequency and heavy rainfall (Hanson and Maul 1991; Schmidt et al. 2001). The second high L_{wn}670 variability episode occurred between late September and late November. This was also the result of storms and rainfall. Particularly, Hurricane Georges passed directly over Key West on September 25, increasing coastal mixing and resuspending large amounts of sediment in the region. During 1998, the Florida Keys lost near 12% of coral cover, suggesting that the combination of stressors, those caused by ENSO event 97-98 (heavy rainfall in spring followed by elevated temperatures in the summer) and Hurricane Georges, might be associated with the decline of coral cover.

A comprehensive analysis of all factors potentially affecting the variability of ocean color is outside of the scope of this study. These factors include wind speed, wave action, disturbance of bottom sediments, rainfall, and river input. In addition, factors that affect the derivation of the ocean color measurements must also be considered, namely atmospheric correction algorithms, suspended sediments and CDOM, bottom reflectance, and sensor issues such as calibration.

My results support the hypothesis that areas with higher ocean color variability had higher coral cover and lower coral cover losses. However, the uncertainties in the data are large. Clearly, more research is needed perhaps using additional water-leaving radiances bands to understand the impact of water color as an index of water quality and its impact on coral health.
2.5. Conclusion

To understand how variability of sediments and water quality can influence coral reef health, satellite-derived normalized water-leaving radiances at two wavelengths (443 nm and 670 nm) were compared with coral cover and coral cover change data from 1998 to 2005. Areas where suspended sediments frequently affect the color of the water, as inferred by high variability in $L_{w670}$, seem to have higher coral cover but not necessarily lower rates of decline. The variability in water clarity during less extreme events, as assessed by $L_{w443}$, did not show a significant influence on the extent or decline in coral cover.

Understanding the factors that affect water color is of great importance to coral reefs and fisheries management. Future research on the effect of water quality on reef health is recommended. This research should include a higher spatial resolution of the ocean color data, including in situ radiance and irradiance observations. MODIS 250 m resolution data, for example, may help to better quantify suspended sediments and more accurately identify the influence of bottom reflectance.
Coral reefs in the Florida Keys have lost nearly 50% of their coral cover in the past ten years. This is an alarming decline, because this is a unique ecosystem that provides essential habitat for hundreds of marine species. In addition, the Florida Keys coral reefs attract thousands of anglers and divers each year, and provide a substantial income for the State of Florida. The tourism industry and fisheries in South Florida closely depend on this valuable resource. Global warming, declining water quality, and coastal development are among the numerous suggested causes for the decline. While the contribution of each is unknown, a combination of stressors most likely affects the Florida Keys coral reef health. Assuming that many of the potential factors stressing the health of coral reefs will not lessen in the near future, coral reef communities will continue to suffer. Presumably some will adapt in an expression of resilience to cope with these stressful conditions.

To account for the pattern of diversity in tropical forests and coral reefs, Connell (1978) developed the “intermediate disturbance hypothesis”. This ecological theory attempts to explain the role of disturbance in maintaining an ecological equilibrium of diversity. Diversity would be maximized at intermediate levels of disturbance, and would decline either with low or high disturbance. For patches where disturbance is high, only a low number of species would be able to colonize substrates and tolerate the high intensities of disturbance. Alternatively, patches with low disturbance would be dominated by species that are more successful competitors. Porter et al. (1999) also proposed that multiple stressors (disturbance) can lower the rates of growth and reproductive capacity of reef-building corals. Such stressors can include nutrient enrichment, turbidity, sedimentation, salinity, and temperature extremes.
To help understand the concept of resilience and how Florida Keys reefs may adapt, the State of Florida Department of Environmental Protection and the Nature Conservancy established the Florida Reef Resilience Program (FRRP) in 2004. This program seeks to determine whether some coral reef species are resistant to damage from catastrophic events, such as coral bleaching. The present study complements the FRRP program by assessing the potential response of coral reefs in the Florida Keys to variability within remotely sensed sea surface temperature (SST) and water quality (using water color as a proxy) between 1998 and 2005.

In this study, I proposed the hypothesis that sites with higher variability in SST and water quality have higher coral cover and lower rates of decline than those where such variability is lower. Low variability was considered to be equivalent to low levels of disturbance, and high variability to high levels of disturbance. While assessing the diversity of coral reefs in the Florida Keys was out of the scope of this research, the extent of benthic coral cover and change in coral cover were compared with levels of variability (disturbance) of SST and water quality.

I found that areas with higher coral cover routinely experience higher SST variability (mean variance >6) and that areas with lower coral cover experience lower variability (mean variance <6). Areas with higher variability of SST also presented relatively lower declines in coral cover (<30%). This suggests that corals dominating in areas with higher variability in SST are better adapted to this type of environment, or simply that this environment is not suitable for other competitors. However, SST clearly is not the only factor that influences coral resilience.

I further compared variability in water clarity with coral cover and cover change, using variability in L_{wn}670 as an index of the concentration of suspended sediments and changes in L_{wn}443 as an index of water clarity. Patch reefs with higher variability in suspended sediments and water clarity generally presented higher coral cover at the end of 2005, as well as high variability in SST. Conversely, offshore deep and offshore shallow reefs had the lowest coral cover, but also showed relatively high variability in turbidity and suspended sediments. No relationship was found between variability of suspended sediment concentration (L_{wn}443) and change in coral cover from 1988 to
2005. Therefore, the results using water-leaving radiance as an index of water quality were not as conclusive as those obtained in the comparisons with SST variability. More, specifically the hypothesis that higher variability in water quality promotes lower rates of decline could not be supported statistically.

The decline of coral reef cover in the FKNMS appeared to depend on the intensity and combination of stress factors. For example, during 1998 the intensity of variability in both SST (mean variance = ~8) and water quality was high (mean variance of Lwn 443 = ~0.2, mean variance of Lwn 670 = ~ 0.6, fig. 3.1), and the corresponding decline in coral cover was devastating (11% of total average coral cover for all stations in 1997 declined to 8.5% of coral cover in 1999, fig. 3.2). This may have been linked to the El Nino Southern Oscillation event of 1997-1998, which affected the study area with heavy rains during the winter of 1997-1998 and high temperatures during summer 1998. Also,
Hurricane Georges affected Florida Bay in fall 1998, increasing coastal mixing and resuspension of sediments.

This study provided an initial understanding of the effects of variability of the ocean environment, namely SST and water quality, on coral reef cover in the Florida Keys. Satellite data proved to be an excellent research tool to complement operational field observations of coral reef cover. However, some of the satellite data has limitations that hamper ecological studies such as what I attempted in this thesis. The AVHRR on NOAA 12, NOAA 15, NOAA 17 AVHRR sensors provided five to 10 thermal images per day, which provided adequate data coverage to create daily composites covering most of the study area. Yet SeaWiFS provided two ocean color images per day, which are subject to clouds, sun-glint, banding, and additional sensor or atmospheric correction errors. Two images are often not enough to create a daily composite with data covering the study area (the FKNMS). Future research incorporating satellite ocean color should also include data from other sensors such as NASA’s MODIS. Also, in situ data should be considered to validate the satellite data. Ultimately it will be necessary to conduct a detailed remote sensing and field study to understand the relationship between the parameters that affect water quality, how these parameters and the reflectance of the
bottom contribute to changes in ocean color, and how satellite-derived ocean color observations can be better used to assess coastal marine environments such as the Florida Keys National Marine Sanctuary. Application of such tools is important because they provide the only means for frequent, repeated synoptic observations over long periods of time.

Coral reef study sites should be carefully chosen so that depth will not confound results based on satellite ocean color data. Bottom reflectance does not interfere with SST estimates because the sensor only receives information from the top few centimeters of the ocean surface.

Continued monitoring of the coral reefs in the Florida Keys in combination with remotely sensed environmental observations can improve understanding of coral reef adaptations to environmental variability. Diversity studies combined with environmental variability can further help by identifying which coral species are better adapted. This may help understand how to protect particular communities. In general, better understanding of the resilience of coral reef species to variability in oceanic conditions will improve the designation and effectiveness of current and future Marine Protected Areas (MPAs).

This study shows that variability of SST and water quality is not always detrimental to coral reef environments. The results only suggest the possibility that one or multiple coral species are better adapted to some degree of reasonable environmental variability, and that this should be considered in planning and design of MPAs. Environmental variability is not easy to control and is often unpredictable. However, anthropogenic stressors (e.g., poorly regulated fishing practices, mangrove destruction or pollution due to coastal development) can be reduced in many areas of the Florida Keys. Limiting the number and level of stressors could help corals increase abundance, better compete with invasive species, or respond to environmental variability. Future research should include quantifying the effects of other disturbance factors, such as fishing disturbance and proximity to urban areas and lead to improved management to reduce further detriment to these important but fragile ecosystems.
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References


