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Advancing spatial-temporal continuity in coral reef ecosystem pattern detection: The morphology, distribution and chemical environments of coral habitats encompassing Coiba National Park, Panamá.

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Abstract. A synoptic perspective of reef biogeochemical dynamics and community structure was revealed using new technologies and methods designed to enable high resolution underwater habitat assessment with non-invasive monitoring capabilities and rapid information output. A towed, chemical sensor platform (TETHYS) and a diver-based, benthic imaging system (SCUBA COP) were developed to compare reef architecture and seafloor morphology across centimeter to kilometer spatial scales, and resolve sub-meter variability in ambient water chemistry across 300 km seascapes. Acoustic bathymetry, stereo-optical imaging, *in-situ* underwater mass spectrometry, and fluorometry data were coupled with precision navigation to enable multi-parameter biogeochemical and structural comparisons of coastal and island coral habitats surrounding Coiba Island, a UNESCO World Heritage site in Pacific Panamá. Baseline chemical data [O_2, CO_2, CH_4, N_2]; and digital 3-D reef mosaics were coupled with SCUBA diver transect data, High Definition video, oceanographic time series from a cabled underwater observatory, Landsat and SeaWiFs satellite imagery to create and validate comprehensive, thematic chemical and benthic habitat maps. This integrated approach shows considerable promise for locating, predicting and quantifying natural and anthropogenic environmental stressors affecting the distribution, diversity and health of tropical coral communities.

Key words: coral reef ecology, benthic optical imaging, biogeochemistry, mass spectrometry, Panamá, Coiba

Introduction

Coral reefs are structurally intricate and complex biogeochemical systems existing in highly dynamic fluid environments. Efforts to link ecologic pattern to process in these variable and adaptive habitats requires precision, multi-scale, spatio-temporal information in order to establish quantitative baselines or accurately identify emergent or alternate stable states (Ratze et al. 2007).

Laboratory methods are limited in their ability to detect gross biogeochemical or metabolic changes of coral reefs over large spatio-temporal scales and may exhibit associated systematic sampling bias. Although SCUBA divers can intensively sample small areas *in-situ*, over brief intervals, physiological constraints makes replication costly (in terms of data density per diver-hour) and inherent information loss occurs through sacrifice in resolution when increasing observational domain (Lam et al. 2006; Hill and Wilkinson 2004). Limited *in-situ* capabilities generate sparse, spatially and temporally disconnected data sets with inadequate overlap, especially when used to corroborate larger scale processes or patterns (Garza-Perez et al. 2004; Mumby et al. 1999).

While coral reef deterioration along the Eastern Tropical Pacific (ETP) coasts of Panamá and Costa Rica were first identified nearly thirty years ago, understanding of the complex biotic-abiotic interplay which resonates and shapes coral communities within this Pacific biological corridor remains elusive (Glynn and Maté 1997; Guzman et al. 2004).

The focus of this manuscript is to convey new, ecologically relevant information emerging from the use of synoptic methods developed to quantify and characterize the architectural and chemical environments of coral communities across multiple temporal and spatial scales. Sites were chosen in the Gulf of Chiriquí (GOC) Panamá among island clusters and coastal zones which geographically delimit the current boundaries of the 216,543 hectare Marine Protected Area (MPA) of the Coiba Island National Park (Fig. 1).

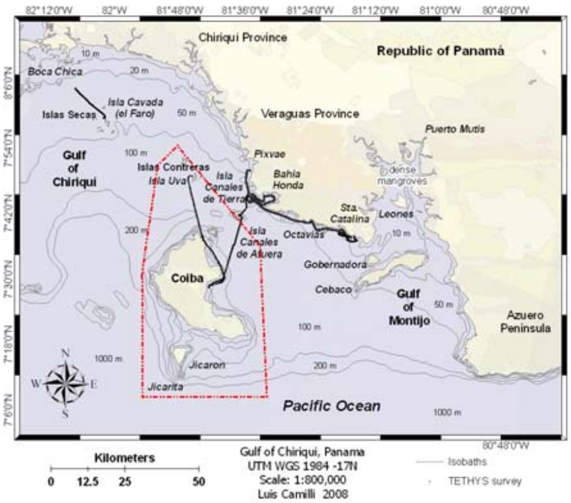

Figure 1: Pacific Panamá Gulf of Chiriquí (GOC) showing Coiba MPA boundary (red dashed line), coarse bathymetry, SCUBA dive sites, and TETHYS towfish survey (black line). Total TETHYS swath distance was 300 km with ≈ 36,000 discrete chemical measurements at 3 m spatial resolution (0.25 m - 15 m) deep.

Material and Methods

Towed, in-situ Mass Spec Chemical Surveys

In February 2007, real time, *in-situ* measurements of chemical species (i.e. O_2, CO_2, CH_4, N_2) chlorophyll-a (chl-a), chromophoric dissolved organic matter (CDOM), salinity, temperature and depth were accomplished using a towed chemical sensing platform equipped with a TETHYS underwater mass spectrometer, CDOM and chl-a fluorometers and a Conductivity, Temperature, Depth (CTD) sensor.

TETHYS was configured to monitor selected ion peaks corresponding to CH_4, H_2S, nitrogen isotope ratios (^{14}N -^{14}N and ^{14}N -^{15}N), O_2, Ar, and CO_2. Additionally, full spectral scans of 1-200 atomic mass units (AMU) enabled identification of hydrocarbons, industrial and toxic compounds. Mass spectrometer data were normalized to Argon which is biologically inert and serves as a natural tracer in ambient seawater. A single beam acoustic depth profiler collected bathymetric data while a Global Positioning System (GPS) device recorded position which was synchronized with TETHYS data based on internally logged time stamps (Camilli et al. 2007).

Average tow velocity was 2.5 m/s with each transect lasting about 6 hours. An oscillating depth or "Tow-Yo" approach was conducted by periodically slowing the boat velocity so that the towfish would perform a vertical cast, and increasing boat velocity until the instrument returned to its near surface depth (- 0.5 m). This technique created a sinusoidal profile of the water column at regular time intervals and was also employed when substantial change was detected in the surface waters.

Automated Diver Imaging Sled and SCUBA surveys

The SCUBA-diver operated Chemical Optical imaging Platform (SCUBA COP) is a self-contained dive sled that collects 12-bit, 1.4 megapixel video-rate stereo image pairs and simultaneously measures water depth, temperature, and dissolved [O_2]. Two laterally mounted and synchronized strobes minimize exposure time and variable effects of ambient lighting. SCUBA COP records mission start and end GPS surface position and continuously records dynamic vehicle trajectory and attitude (360° angular motion over 3 axes). Altitude above sea floor is triangulated based on stereo field of view (Camilli et al. 2007).

Seven dive locations were chosen to represent GOC areas with coral cover, and a stratified approach spatially randomized transects at each dive site using a list of random compass bearings and distances (10-100 m) from the dive vessel. Three, 50 m, tape-based linear transects per site were oriented perpendicular to shore to standardize swath coverage. Each transect was spaced a minimum of 20 m apart. Serial transects were captured at 2 m altitudes by one diver equipped with a Sony HDR-UX1 digital High Definition (HD) video camera followed by a second diver operating the SCUBA COP stereo imaging system. A third diver employing a Point Intercept Transect (PIT) method manually surveyed the same transects, defining 10 benthic categories at 0.5 m intervals below the tape (Reef Check 2004; Page et al. 2001).

Results

Reef Water Chemistry in the Gulf of Chiriquí

At an average tow depth of 2 m across the GOC, mean water temperature was 28.14 °C and salinity was 31.95 practical salinity units (psu) (N=35,953). Temperature and salinity for all coastal surveys were 28.7 °C and 31.85 psu, while offshore regions measured 29.9°C and 31.24 psu respectively.

Contrary to expectations, coastal transects over a shelf ≤ 30 m deep, homogeneously exhibited, lower temperature and higher salinity than offshore transects over deep water (≥ 50 m). The Panamá LJL Underwater Tropical Observatory (PLUTO), located at 18 m depth within the coastal survey area concordantly measured high frequency time series (≈10 min) oscillations in temperature ranging from 16° C to 28°C, and salinity fluctuations ranging from 27 to 32 psu over 3 m tidal amplitudes. Preliminary seiche calculations using measured wind velocity and water depth suggest that this effect is not a result of localized surface wind stress.

Low levels of dissolved O_2 were noticed between Canales de Afuera and Canales de Tierra islands and between the Islas Secas group to Boca Chica.

Comparatively high O_2 levels were observed near Isla Uvas and again northwest of Isla Coiba. Average [chl-a] for inter - island transects were higher 0.24 µg/L (+/- SD 0.02) than coastal transects 0.16 µg /L (+/- SD 0.06). The transect leg from Boca Chica to the Islas Secas group contained the highest mean [chl-a] 0.31 µg /L (+/- SD 0.05). Northwest along the coast, near the bay of Pixvae, chlorophyll was often near zero 0.05 µg /L (+/- SD 0.05) and low again going east along the coast until Santa Catalina where values increased to 0.20 µg /L (+/- SD 0.08).

Along the coast, CDOM concentrations averaged 5.50 Quinine Sulfate Units (QSU), and 2.87 QSU offshore. CDOM and Chl-a adjacent to offshore island reefs are shown in Fig. 2. Strong vertical gradients and localized anomalies dominated coastal regions of the Eastern GOC with CDOM reaching an order of magnitude greater (≥50 QSU) in the bay of Bahia Honda.

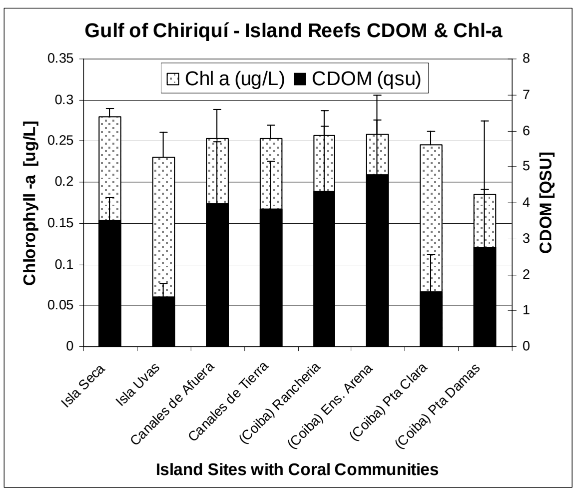

Figure 2: Comparison of mean chlorophyll-a [µg/L] and CDOM Quinine Sulfate Units [QSU] concentrations from TETHYS TowFish surveys of offshore islands in the Gulf of Chiriquí (≈15,000 samples). Error bars represent 1st standard deviation.

Survey transects provide evidence that the variability of nutrient mixing in these water masses can be extreme (Fig. 3). For example, a small plume of brackish water with salinity < 10 psu and high CH_4 was found subsurface near the coast of Santa Catalina (Fig. 4). Nitrogen isotopic (^{15}N) enrichment (i.e. low ^{14}N : ^{15}N) patterns were also observed in the western GOC between the Secas Islands and the Boca Chica mangrove mainland. A negative correlation between CO_2 and salinity ($r = -0.451$; $n = 842$) suggests that freshwater input near island regions could be more important in determining CO_2 levels than pelagic water sources where carbon would ostensibly originate from atmospheric CO_2 drawdown. Offshore subsurface CDOM weakly correlates with salinity ($r = +0.245$; $n = 842$). The reverse is true for the strong negative correlation ($r = -0.805$; $n = 260$) between CDOM and salinity in the central GOC, supporting the idea that dissolved organic material input to these reefs may originate primarily from terrestrial sources.

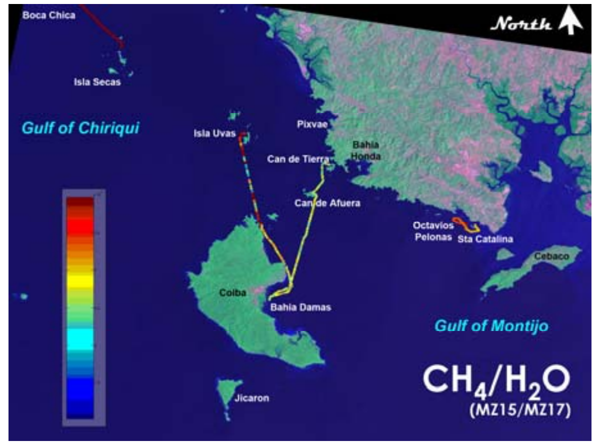

Figure 3: Example of synoptic chemical habitat maps generated for each bioactive parameter measured across survey areas. Color gradients indicate concentrations [mass (M) to charge (Z) ratios] of each element. Simultaneous chemical and GPS data were georectified and integrated into Landsat TM year 2000 satellite imagery to produce high resolution GIS composite images.

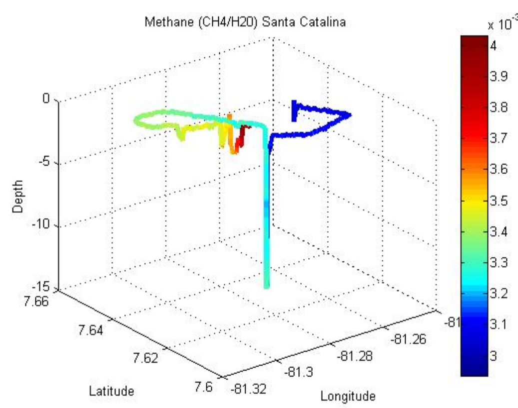

Figure 4: TETHYS sinusoidal profile and deep cast revealing (3-D) methane concentrations in the water column surrounding the island (and village) of Santa Catalina (reference Fig. 3). Color gradient areas in red indicate higher levels of methane (M/Z) and areas in blue indicate lower levels (dimensionless units). Depth = meters; latitude / longitude = degree-decimal-minute.

SCUBA surveys results

For the purposes of standardizing comparisons between methods, percent cover of each of ten categories was used to characterize the benthic substrate and sessile organisms across dive sites. The Reef Check method tends to overestimate sand cover and underestimate algal cover and coral rubble (Fig. 5). Both methods function similarly well in determining hard coral, silt, and rhodolith percent cover. Structurally complex, carbonate architectures dominated by *Pocillopora damicornis* and *P. Elegans* were encountered on northern (unexposed) shores of islands in shallow (<10 m) waters over a continuous sloping shelf (i.e. Islas Contreras and Islas Uvas). More diverse, discontinuous and patchy coral communities were found on shallow rocky shelves on southern (wave exposed) shores. Soft coral, gorgonian and sponge communities were most often encountered in large boulder areas with swift currents (≥ 15 cm/s) and colder water (Δ ≥ -5°C) at depths 15 to 20 m. Hard corals, if present, existed in isolated patches closer to the surface, interspersed between heavily encrusted boulders. A filamentous red-brown algae (Cyanophyte) covered sandy areas (esp. Bahia Damas, Coiba) and stable sea grass communities were conspicuously absent in shallow sandy areas. Dense calcareous red algae (Rhodolith) beds covered shallow areas of some islands; (i.e. 40 % cover in Isla Canales de Afuera). Hard coral species encountered across dive surveys include members of Agariciidae: *Gardineroseris planulata, Pavona clavus, P. gigantea, P. varians, P. chiriquiensis*, *P. frondifera*, *P. maldivensis;* Pocilloporidae: *Pocillopora elegans, P. damicornis*, *P. capitata, P. eydouxi;* Poritidae: *Porites lobata, P. panamensis;* Siderastreidae: *Psammacora stellata;* Fungiidae: *Cycloseris curvata; Milleporadea*: *Millepora intricata;* Dendrophyllidae: *Tubastraea coccinea*.

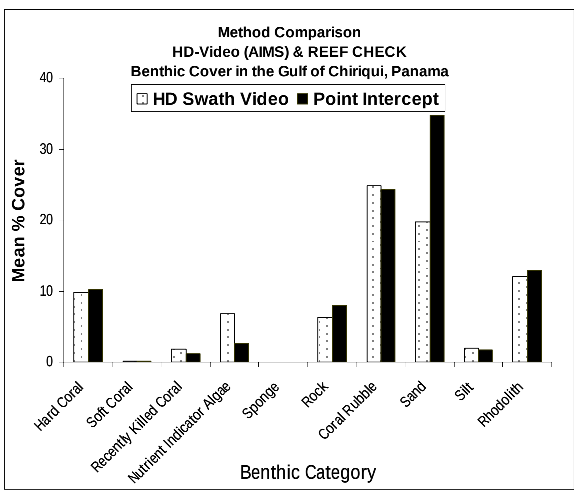

Figure 5: Reef Check (2004) and High Definition video (Australian Institute of Marine Science video protocol) using identical transects to assess 10 benthic cover categories across 7 dive sites in GOC.

The HD-video analysis (Fig. 6) indicates Isla Uvas and Isla Canales de Afuera with equally high coral cover (18.4%). Isla Canales de Tierra, near the mainland, was (16.6%). El Foro (Islas Secas) was (4.6%) - the lowest of all the offshore islands. Isla Managua located within the protected coastal bay of Bahia Honda, exhibited even lower (1.3%) coral cover when compared to Punta Miel (4.4%) at the western headland of the same bay.

Significantly more area was surveyed with the SCUBA COP than with HD video and PIT methods. Approximately 500 GB of digital stereo imagery were collected during 6 diving days corresponding to nearly 7 hrs of bottom imagery and 5 km linear data and representing 7500 m^2 area coverage. At this point, the mosaic swath processing can be divided into strips and applied to any subsection of the data ranging from 10s to 100s of square meters. Due to the fact that morphologically different coral species possess uniquely shaped surfaces, texture-based decision algorithms can be employed to automate coral classification from machine vision data. The subset of SCUBA COP mosaic swaths corresponding to the structured linear transects (i.e. PIT and HD video) are currently being used to create and validate automated feature segmentation and classification routines.

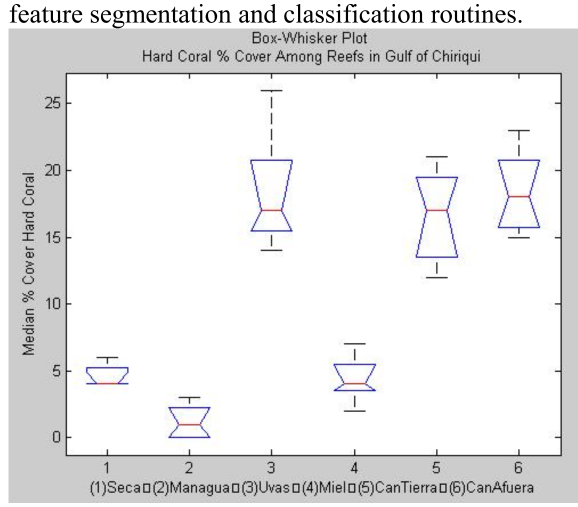

Figure 6: Variability of hard coral % cover among reef sites in the Gulf of Chiriquí. Lower and upper lines of each "box" = 25th and 75th percentiles. Distance between top and bottom = interquartile range. Horizontal middle line = sample median (skewness). Lines above and below the box = total sample extent. Notches in the box = confidence interval about the sample median.

Discussion

Multi-parameter TETHYS data imply that inter-island surface water chemistry (0-12 m) in the eastern GOC is relatively well mixed while shallow coastal areas are periodically exposed to cold water pulses during the dry season (boreal winter). Perhaps deep water originating in the adjacent Gulf of Panamá (or further offshore) is entrained in subsurface circulations that seasonally manifest as internal waves, eroding the thermocline and shoaling turbulently over shallow coastal bathymetry with added effect from orographic lift during large amplitude tides. Regardless of the mechanism, seasonal cold water pulses are regularly being delivered to coral communities, colder and more sustained than previously considered (*sensu*: Glynn and Maté 1997). Although these phenomena are likely influencing reef community structure and associated biochemical processes, unfortunately, subsurface mixing of cold water masses with warmer surface waters (≈10 m depth), and the spatial aliasing inherent in satellite sensors impairs routine remote observation. The finer spatial-temporal resolution afforded by the TETHYS towfish allowed synoptic visualization of these winter, dry season temperature/salinity patterns and the associated primary productivity in subsurface water across a >100 km swath (Fig. 7).

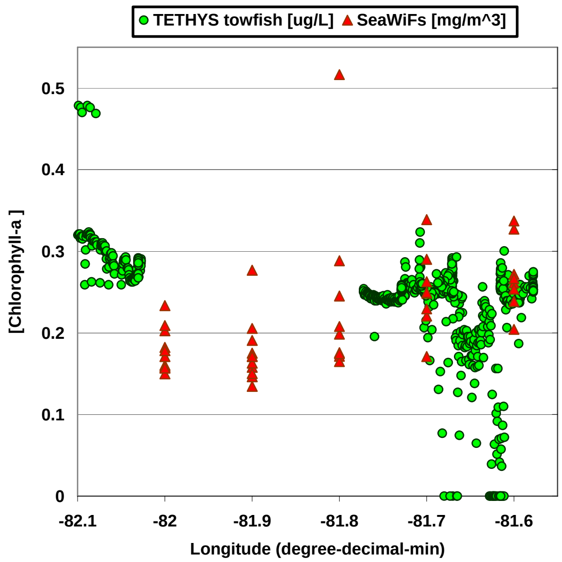

Figure 7: Comparison of *in-situ* TETHYS towfish and remotely-sensed SeaWiFs satellite [chl-a] data plotted along a longitudinal gradient during a time scale of 2 weeks in February 2007. Spatial resolution of SeaWiFs = 9 km^2 and finer spatial resolution of TETHYS towfish = 3 m^2. Data are reported in equivalent units [µg/L] = [mg/m^3]. Coarser SeaWiFs chlorophyll estimates provide an accurate upper limit constraint on sea surface chl-a, but are not able to substantially resolve smaller scale spatial-temporal dynamics over the same domain.

Contextually elevated CH_4, ^{15}N, CO_2, and [chl-a] coupled with lower O_2, suggests more eutrophic waters extending from the Boca Chica mainland into the central GOC. Although stretches of oligotrophic water were observed along the coast north and east of Coiba during this dry season survey, the risk of eutrophication along the Coiba Island corridor could be elevated especially during the wet season. Panamá experiences high seasonal rainfall (>3000 mm/yr) and these reefs could be severely impacted if corals are exposed to chronic runoff of nutrients originating from soil erosion, fertilizers or untreated sewage. Detrimental effects of NO_3^- enrichment (Schlöder and D'Croz 2004) in *P. damicornis* might be of great relevance for local conservation because it is the major reef-building coral in the ETP; a biotope known for intrinsically low coral diversity. GIS analysis of year 2000 Panamá Census data indicates >103,000 people inhabit the Gulf of Montijo drainage basin with 24 major tributaries eventually flowing into the eastern GOC (L. Camilli, unpub. data). Agricultural land use pressure, herbicides, erosion, unregulated coastal construction, mangrove deforestation, and increases in septic effluent in surrounding areas poses a tangible threat to the biological integrity of coral reefs ecologically linked with the Coiba MPA.

Coral reefs are complex adaptive systems that can experience accelerated habitat change due to their proximity to natural and anthropogenic disturbances worldwide. Semi-automated, *in-situ* chemical and optical sensor innovation reduce survey time and enhance the ability to effectively focus and tune experimental efforts. By resolving multi-dimensional ecologic and oceanographic variability in greater detail, the novel analytic methods demonstrated in this project complement remote sensing techniques, field manipulations, laboratory experiments, and become a critical nexus in accurately coupling pattern to process in the ocean environment.

Acknowledgements
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