Hydrodynamic Controls on Acoustical and Optical Water Properties in Tropical Reefs

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LONG-TERM GOALS

The general objective of the work underway is to develop a baseline characterization of the spatial and temporal variability in optical/acoustical water properties for tropical island environments in response to variations in physical forcing.

OBJECTIVES

Specifically, the project aims to address the following questions:

- What are the dominant space and time scales for variability in optical and acoustical water properties for tropical island reef environments?
- How do these vary for different reef zones, including forereef, reef flat, lagoon and channel areas?
- What are the dominant hydrodynamic controls across different reef environments?

Tropical coral health can be significantly affected by sedimentation that can limit light availability, impact recruitment and bury coral colonies. The ongoing work will improve understanding of the dynamical processes that affect variability in optical and hydrodynamic properties for these important environments.

APPROACH

A two-week long set of focused field experiments was completed in March 2012 targeting temporal resolution of optical and acoustical water properties and flow hydrodynamics over a variety of reef environments with concurrent AUV-based spatial mapping. The field study site was located in the Republic of Palau (figure 1a), an island system including complex barrier reefs and multiple lagoon system. Palau has been the site of ongoing ONR-funded collaborative field work by the PIs, carried out in collaboration with UCSD SIO (PI: Terrill) and the Coral Reef Research Foundation in Koror (PI: Colin).

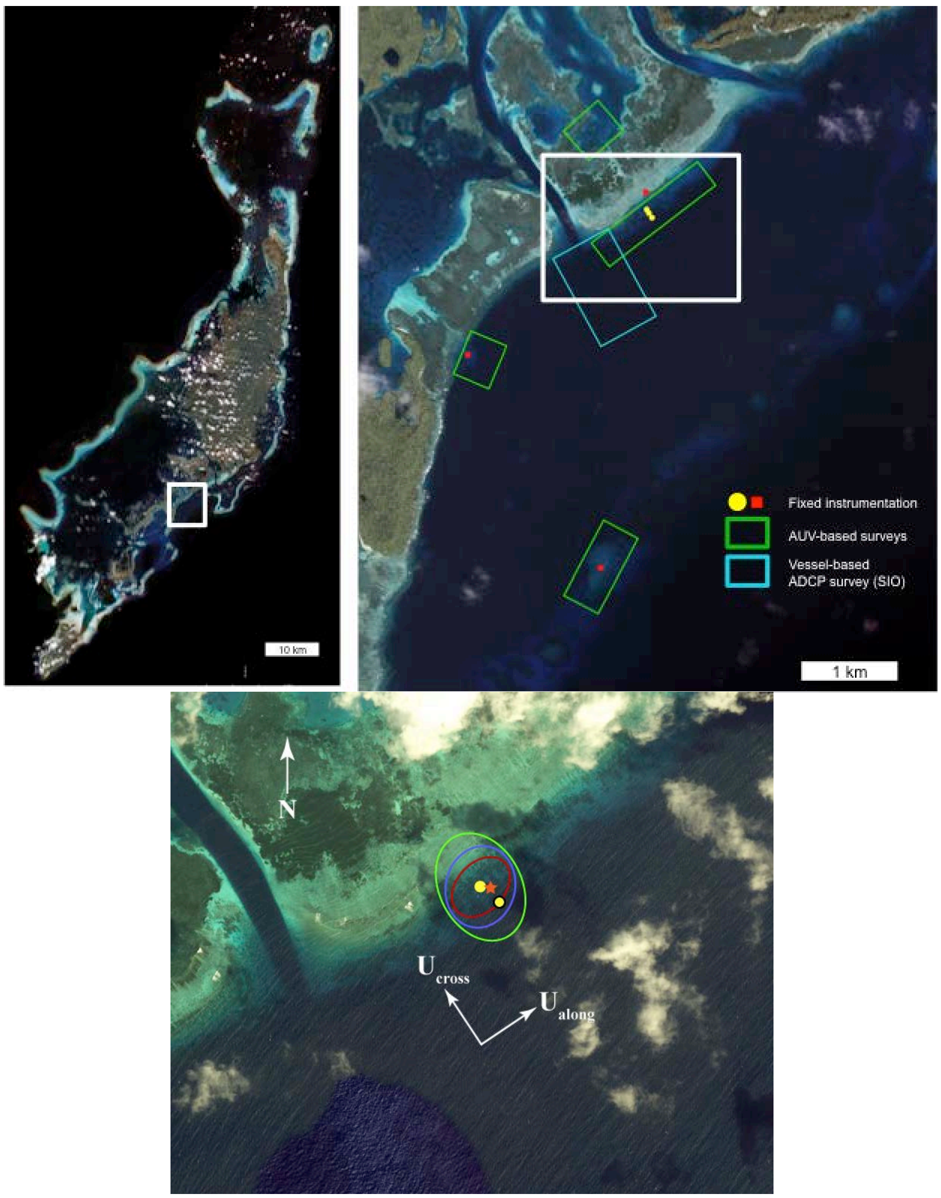

Figure 1 – A) Republic of Palau with study area highlighted in white. B) Study area with instrumentation sites and AUV, vessel-based survey areas highlighted. C) Close-up of Ngadarak Reef site, with ADCP/Tchain sites (yellow) and ADV spar (orange). Current ellipses show variation in cross-shore flow for near-bed (red), mid-column (blue) and near-surface (green) flow velocities.

The Palau observations included fixed instrumentation deployments and multiple AUV and vessel based measurements along the eastern side of the island system on a southeast facing narrow forereef in the vicinity of Ngadarak Reef (figure 1b). Bottom mounted instrumentation featured a 3m vertical spar with 3 ADVs along with a nearby (~3m) vertical array of optical sensors at the 10m isobath to enable definition of the source of particles influencing the optical and acoustical backscatter and to quantify the impact particles have on remote sensing capabilities. Optical instrumentation included a Wetlabs BB2F OBS sensor, a Wetlabs 3 channel/3 angle ECO Volume Scattering Function (VSF), and a Wetlabs AC-9 sensor. ADCPs with co-located thermistor chains were located at the 8m (1200kHz) and 17.5m (300kHz) isobaths to resolve cross-shore gradients. A bottom lander, including a 1200kHz ADCP, 6MHz ADV and a 2 channel OBS sensor, was deployed at multiple locations for short (1-2 day) periods.

AUV surveys were conducted daily to resolve spatial patterns in ABS/OBS and in flow structure, at varying times in the diurnal cycle. Several multi-vehicle surveys were carried out to improve spatio-temporal coverage. In addition vessel based CTD/PAR profiling was conducted during AUV missions. UCSD SIO also carried out vessel-based ADCP surveys of the nearby (southeast) channel during the ebb tide.

A second set of observations, focused on hydrodynamics, was carried out on the west coast of Oahu, Hawaii in September 2013 as part of collaborative work with Mark Merrifield (U Hawaii).

In addition, a key component of the work is to continue analysis of current bed stress in coral reef environments, using observations from Oahu, Palau and Guam. The project is providing partial support for a postdoctoral researcher, Audric Collignon, who is focusing on analysis of turbulence data and who has also participated in the recent Oahu field work.

WORK COMPLETED

Year 1 of the work included field observations in spring 2012, preprocessing and initial time series analysis for fixed and mobile data sets. Year 2 has included in-depth analysis of relationships between optical, acoustical and hydrodynamic data, as described below. In addition, year 2 included completion of additional field observations on the west coast of Oahu, Hawaii, targeting AUV-based roughness, hydrodynamics and optics observations with fixed sites measuring turbulence and ABS variability. Additional analysis in year 2 has also focused on bed stress and roughness observations from previous ONR-funded work in Palau and Oahu along with additional data sets from Guam. Results from the work will be presented at the AGU/ASLO Ocean Sciences meeting in Honolulu in Feb. 2014 with a research journal article presently in preparation.

RESULTS

Conditions during the March 2012 experiment included strong southeasterly winds (onshore at the experiment site) during the initial portion with accompanying increased waves, followed by a period of weak winds and rapidly diminishing swell. Currents were predominantly alongshore, but with a significant cross-shore flow component, which was surface intensified during the outflowing tide. The effect of the surface cross-shore flow is evident in the current ellipses in Figure 1C. Strong high-frequency (~hr^{-1}) pulses were observed in the alongshore current during the ebb that are possibly indicative of instability in the channel outflow to the southwest.

Relative acoustic backscatter (ABS) profiles were derived from individual ADCP beam echo intensity correcting for range and absorption using the sonar equation (Deines, 1999). Observed ABS patterns are similar at the 1200kHz ADCP (8m) and the 300kHz ADCP (17.5m). Depth averaged 1200kHz ABS for the 8m site averaged by time of day (Figure 2) reveals an apparent influence of the diel cycle, with low backscatter during midday hours with maxima at dawn and dusk. Although the diel cycle is difficult to separate conclusively from tidal influences due to the relatively short data window, the variation in 1200kHz ABS by time of day is much more pronounced relative to variations by tidal phase (Figure 2), which suggests that the former is dominant.

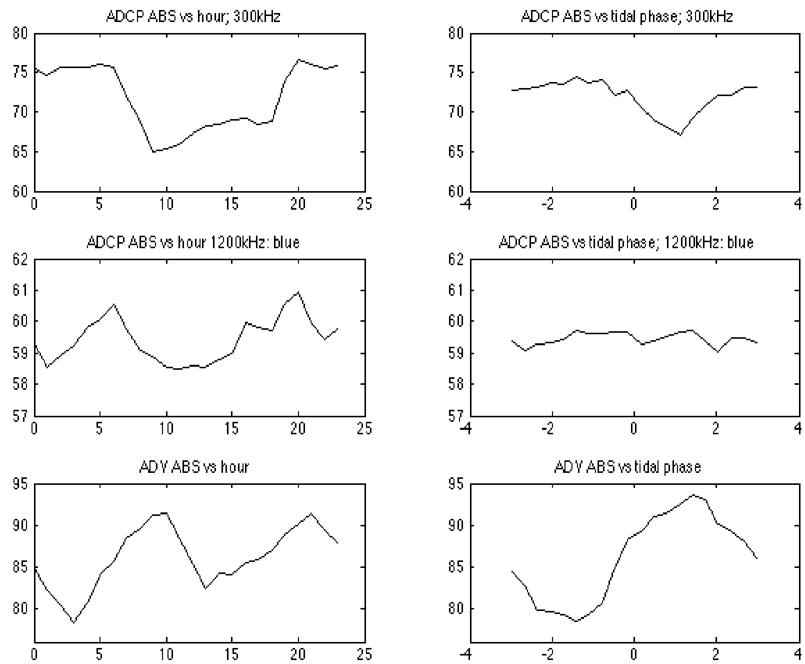

Figure 2 – Variation in ABS vs time of day (left column) and M2 tidal phase (right column) for 300kHz (top), 1200kHz (middle), and 6MHz (bottom).

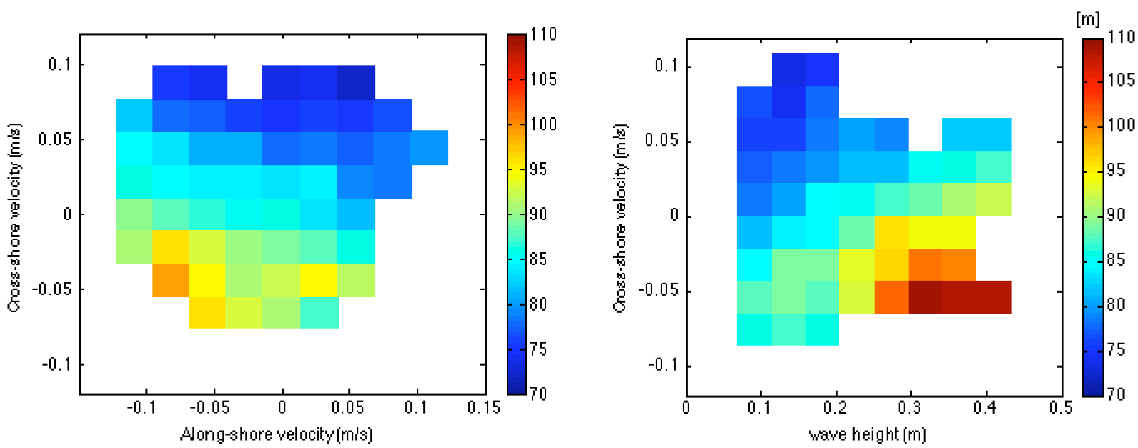

Figure 3 – A): 6Mhz ABS (color) (40 minute lag) vs along, cross-shore velocity. B) 6MHz ABS (color) (40 minute lag) vs cross-shore velocity, wave height. ABS units are arbitrary.

ABS was also obtained at 6MHz, 2 and 3m above the bed from the ADVs located at the 10m isobath a short distance (~30m) from the 8m 1200kHz ADCP. The higher frequency backscatter from the 3m ADV (Figure 2) shows a clearer tidal signal, in contrast with that from the two ADCPs. 6MHz ABS shows a strong directional dependence with higher values, on average, for offshore flow. Variations in 6MHz ABS lag the cross-shore flow by 30-60 minutes as might be expected for advection from a remote source. Figure 3A shows the variation in 6MHz ABS (lagged by 40 minutes) with current direction, consistent with an onshore source. The high frequency ABS also shows significant variation with wave height, however. Figure 3B shows the cross-shore dependence modulated by wave height. The shoreward source for 6MHz ABS increases in strength with increasing wave height suggesting wave resuspension of fine particulates on the reef flat as a mechanism for controlling backscatter. Optical backscatter (OBS) in the red, green and blue bands (not shown) all follow the high frequency ABS closely with the same wave and directional dependence seen in figure 3.

Optical scattering, calculated from observations of absorption, and attenuation, shows more complex variations, but with a tidal influence reflecting asymmetry in the flow patterns. Optical scattering show a decrease with increasing wave height, in contrast with OBS. The relationship between OBS and total scattering further indicates that, during these periods, not only do the bulk particle signals change, but that the particle size also varies. Ratios of OBS for the different colors vary significantly with wave forcing.

Spatial OBS observations obtained via REMUS-100 surveys illustrate the cross-shore and vertical variation and indicate a shoreward source for particulates (Figure 4). Observations also highlight spatial variability in the optical and acoustic characteristics.

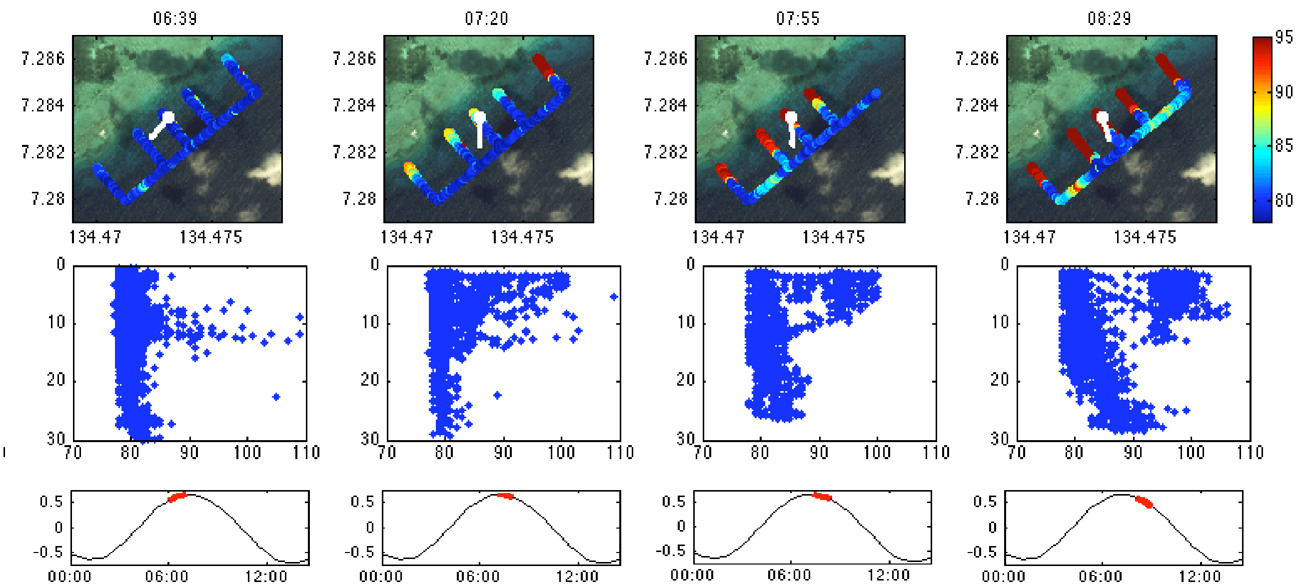

Figure 4 – Top row: AUV track over aerial image of Ngadarak forereef (Palau) for successive survey passes. Color indicates optical backscatter at 470nm (arb units). Bathymetry increases from 0-1 m on upper left to >100m on lower right. White circle indicates fixed instrument package location. White arrow indicates average current vector during each survey leg. Middle row: AUV-based optical backscatter (arb. units) vs depth corresponding to upper panels. Bottom row: Tidal variation with corresponding period highlighted in red.

The direct effect of the variability in the hydrodynamically controlled inherent optical properties on remote sensing is also being investigated, including LIDAR penetration depth and traditional ocean color remote sensing techniques to discriminate bottom types. Calculations of remote sensing reflectance (R_{rs}) using the radiative transfer model HydroLight with the optical measurements as input variables indicates variations of 30% over the observational period (figure 5). These estimates, based on measurements at mid-depth, are likely conservative given that the highest ABS values were observed at the surface. Optical penetration depth is also estimated from optical parameters using Hydrolight. For particular wave conditions, optical depth is linearly related to 6MHz ABS, although the linear trend is offset by variations in wave height. This results in the variation shown in Figure 6 where optical depth *increases* with increasing wave forcing and onshore flow. The key to this variation is a dependence on particle size implied by the changes in ratio of backscattering to total scatter described above. The observations suggest that hydrodynamic forcing can result in significant, measurable variations in remotely sensed variables. This approach may link remote sensing to the physical dynamics for use as a tool in these reef systems.

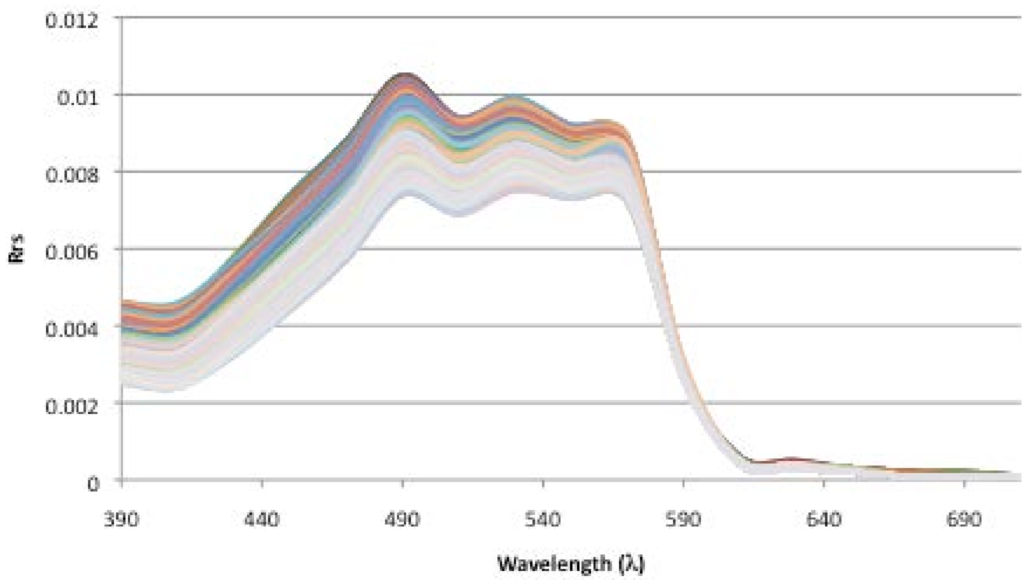

Figure 5 – Remote sensing reflectance spectra for observational period, as derived using HydroLight from measured optical data.

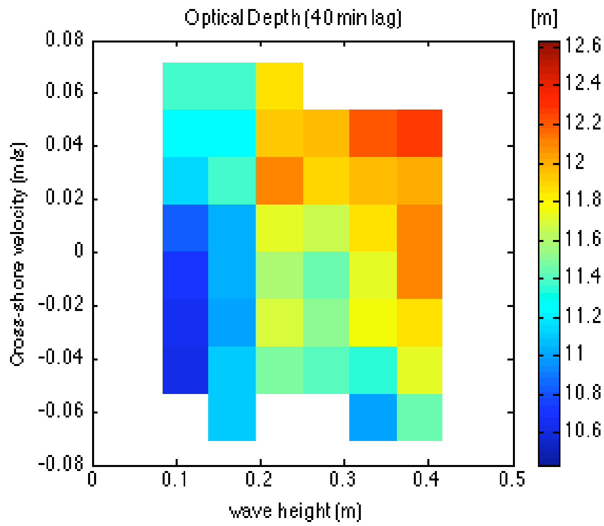

Figure 6 – Optical depth (40 min lag), as derived using HydroLight from measured optical data versus cross-shore velocity (y) and wave height (x) indicating the role of physical forcing in remote sensing characteristics.

The spectral signature of the optical variations was consistent with that observed for whiting events as described by Dierssen et al 2009. The spectra can be attributed to micron-sized aragonite particles. The backscatter variation across the spectra related earlier to wave forcing has been previously observed for whiting events (Dierssen et al. 2009, McKee and Cunningham, 2005) and has been suggested as resulting from a dominance of a single particle type.

Ongoing analysis of previous field data sets has included estimates of bed friction coefficients and the apparent roughness height associated with the steady bed stress flow estimated by logarithmic fits to ADCP velocity profiles. These estimates show a dependence on the current/wave velocity ratio, decreasing as the ratio increases. The magnitude of the friction factor estimates is surprisingly close among sites, despite different bed morphologies. Analytical models of combined current and wave motions over rough beds (Grant and Madsen 1979; Christoffersen and Jonsson 1985) yield estimates consistent with these observations, which suggests that they are applicable in these high roughness environments.

IMPACT/APPLICATIONS

Coral reefs are ecologically rich zones supporting vast ecosystems. They are a dominant feature of coastal environments between the latitudes of 25S and 25N (Hoegh-Guldberg 1999). Tropical coral health can be significantly affected by sedimentation that can limit light availability, impact recruitment and bury coral colonies (Ogston et al. 2004, Fabricius 2005). The extent to which sedimentation affects benthic communities is dependent on temporal and spatial extent of events combined with local hydrodynamic characteristics. The work underway will improve understanding of the dynamical processes that affect variability in optical and hydrodynamic properties for these important environments.

The variations in measured and derived optical and acoustical properties described above suggest that hydrodynamic forcing can introduce significant, measurable changes in remotely sensed variables.

Accurate assessment and prediction of optical and acoustic properties is critical for remote sensing applications. The work described above is establishing a general baseline of the variability in these critical water properties and to resolve the interactions with physical and biological forcing for tropical environments. The observations and analysis presently underway will also enable more general characterization of bed morphologies in reef zones and will lay a foundation for remote sensing of bed characteristics from aerial and satellite imagery. Furthermore, the observations suggest that remote sensing can also be useful in assessing hydrodynamic characteristics for inaccessible reef areas.

RELATED PROJECTS

The project is being carried out concurrently and in close collaboration with other ONR funded work in Palau (Moline, Terrill), leveraging much of the equipment required for this study. The work described here has also been carried out in parallel to a separate, complementary ONR funded project that is targeting parameterization of wave and current drag for flow over complex roughness. Some of the AUV surveys and hydrodynamics observations described above provide data relevant to both projects and some analysis efforts overlap. Further observations in support of this project will also yield useful data sets for the reef roughness work.

The work is also being coordinated with NSF and Army Corps funded projects (PI: Merrifield) targeting wave transformation and coastal flooding for island shorelines. Project PIs are collaborating to carry out further observations that will enable extension of the work described here and providing an additional data set for analysis.

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