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Photosynthesis as a Possible Source of Gas Bubbles in Shallow Sandy Coastal Sediments

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LONG-TERM GOALS

Our long-term interests involve the possibility that biogenic activity can influence acoustic scattering at the water column-seabed interface and the propagation of sound in and over a sandy substrate in a shallow-water coastal marine environment. Evidence from laboratory studies on sand collected from the surf zone clearly demonstrates that gas bubbles can be formed when photosynthesis by benthic microalgae causes pore water to become supersaturated with oxygen.

OBJECTIVES

The next logical step is to determine whether this phenomenon occurs in the coastal ocean. The near-term objective of the work is to determine whether photosynthesis produces conditions that lead to the formation of oxygen bubbles in the top few millimeters of shallow sandy coastal sediments, and if it does, how such bubbles change the acoustic reflectivity of the seabed.

APPROACH

In the laboratory, exposure of natural sand from a beach in Panama City, FL, was observed to scatter broadband sound in different amounts throughout a diel cycle (Figure 1).

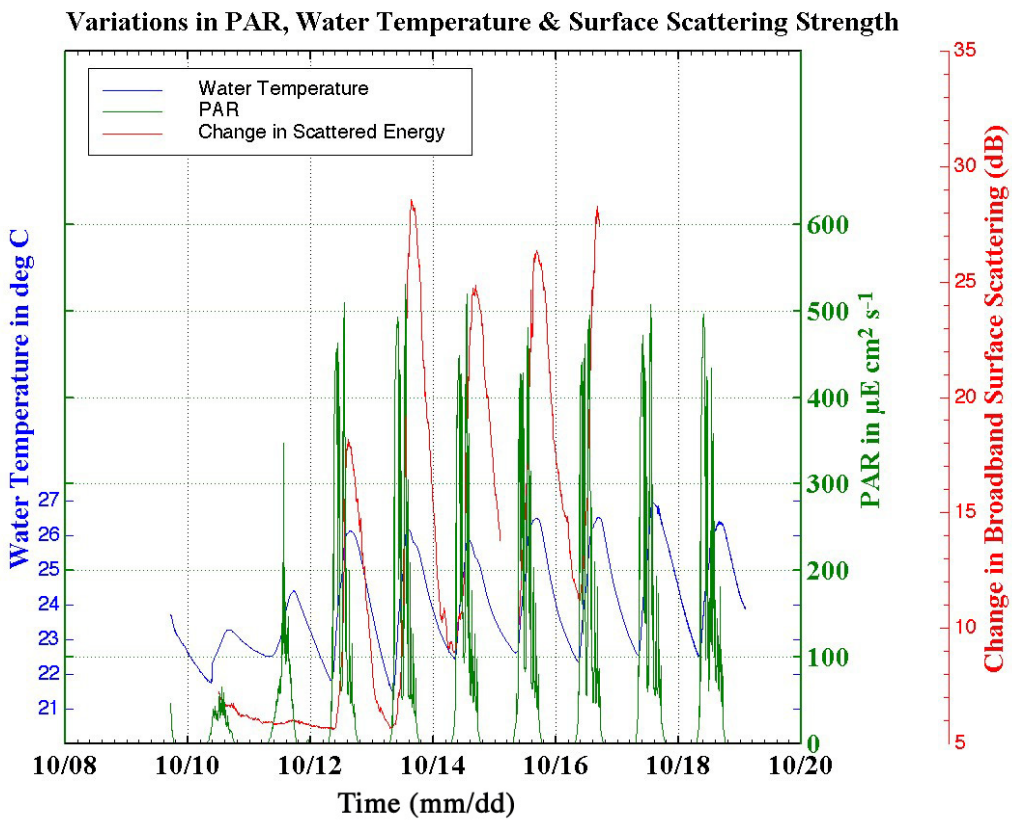

Figure 1: Diel variations in the broadband (100 kHz to 900 kHz) acoustical scattering from a bed of sand (red), the water temperature (blue), and photosynthetically active radiation (green) as measured in a laboratory aquarium exposed to natural sunlight via a neutral density film over a glass window. The resulting light levels simulated a depth of ca. 20 m. Water temperature (blue) was also measured, and the changes were determined to be too small to have caused the increases in scattering. The sand was from a beach in Panama City, FL. A 30 dB change in scattering is equivalent to an increase of 1000 times.

The variations in scattered sound were synchronized with, but lagged, diel changes in light levels incident on the bed of sand. Bubbles were seen on the surface of the sand during periods of high scattering. This observation strongly suggests that photosynthesis created sufficient oxygen to cause supersaturation in the pores between the sand grains. This eventually led to the formation of small bubbles that then migrated to the sediment-water interface, coalescing during and after the migration to form larger bubbles that were visible to the naked eye. The acoustic scattering from the bubbles then caused increases in the broadband scattering from the bed of sand, as more bubbles were formed and those present grew in size during the day. In the absence of sunlight, the bubble numbers and sizes were reduced, either by release of the bubbles when their growth or buoyancy exceeded the forces

keeping them in place on the sand surface or by reabsorption of the gas into the water after oxygen production slowed and finally ceased during the dark hours. Additional details regarding the laboratory experiment can be found in Holliday *et al.* (2004) and Holliday (2009).

Our objective is to determine whether the phenomenon observed in the laboratory also occurs in the sea. We have developed equipment that will allow us to obtain backscattering data from the seabed and to examine it for the temporal changes that would be expected should the production of oxygen be sufficient to produce bubbles. We have also developed equipment (i.e., a time-lapse underwater camera) to investigate other possibilities (e.g., biological roughening).

We have tested our equipment at a 5-m deep site on the north Florida shelf in the Gulf of Mexico (29° 52.169' N, 84° 26.428' W). This site is well documented (Teasdale, Vopel, and Thistle, 2004). The seabed is well-sorted, unconsolidated medium sand. Storms occasionally cause sediment resuspension and ripple fields can be created. In order to get unambiguous answers regarding the source of any observed change in scattering, we will deploy a time-lapse camera to record conditions in the field of view of the acoustic sensor to allow us to separate macroscale physical changes in the bottom topography from biological processes other than bubble production that lead to changes in the acoustic reflectivity. We also collected sediment samples from the upper few mm of sand to identify the dominant taxa of benthic microalgae present.

Charles Greenlaw prepared and bench tested the acoustic (Figure 2) and optical instrumentation for this research project. David Thistle from Florida State University (FSU) tested the equipment in the field and is preparing the benthic lander (Figure 3) for making oxygen profiles in the sediment, and has collected samples for Jan Rines (Graduate School of Oceanography / University of Rhode Island (GSO/URI) to identify the benthic microalgae in the samples. Following the untimely death of Dr. D.V. Holliday, the remaining team members are sharing the responsibility of analyzing data and preparing such presentations and publications as may be merited based on our results.

Figure 2: The Sand Scan acoustic sensor consists of a broadband acoustic transducer, a small grey cylinder shown here on a movable arm at the upper left of the instrument. The white pressure case contains the electronics necessary to transmit a sequence of 200-microsecond pulses at several discrete frequencies between ca 0.16 and 0.40 MHz, receive the echoes from a small area on the seabed, and store digital representations of the received bottom reverberation waveforms. The black cylinder contains batteries. For scale, the tiles on the lab floor were 1 foot on each side.

Figure 3: Shown here on shipboard, FSU's battery powered, autonomous, benthic lander measures oxygen-concentration profiles in unconsolidated sandy sediments. Up to four oxygen probes mounted at the bottom of the black cylinder are mechanically driven into the sediment and measurements are made at sub-millimeter intervals. An internal computer controls a motor via software that is programmed to collect a profile at time and depth intervals specified before the lander is deployed on the sea floor. Data are recorded internally and retrieved when the lander is recovered. The ring on top of the lander is used for attaching a hook or line during deployment and recovery operations. For scale, the black electronics cylinder is ~ 6 inches in diameter.

WORK COMPLETED

We have modified the SandScan acoustic sensor to provide the capability of echo ranging over a slant range of 1.7 m. The range resolution is now *ca*. 15 cm, depending on the speed of sound near the seabed. The sensor sequentially transmits 200-microsecond pulses at seven discrete frequencies between 0.220 and 0.335 MHz, which spans much of the range of frequencies that produced large

scattering strength changes in the laboratory experiment. Sufficient battery power and memory was installed to allow recording of a complete data set of 24 pings per frequency every 20 minutes for about a week. The benthic lander has also been refurbished and configured for use in this project.

SandScan was deployed on four occasions in 2010 prior to the writing of this report and is deployed for a fifth data session at this time. Two deployments (March and August) resulted in no data due to equipment failures. Two deployments (April and June) netted ten days of bottom scattering data. On the last deployment (August), the light meter's data logger failed, and no PAR data were recorded. The system is currently deployed with a replacement data logger for PAR. Our time-lapse camera is also deployed this time.

SandScan outputs raw echo amplitude samples in digital format to the associated acoustic datalogger. These amplitudes were downloaded and processed post-deployment. Normal processing included estimating the mean bottom backscattering echo in each range bin and correcting each channel for system response. The expectation was that the bottom backscattering echoes would show some temporal correlation with incident light as measured by the PAR sensor near the SandScan.

A typical result is shown in Figure 4. Here the mean echo intensities are plotted (as dots) for every data set over the four days of data collection in April, 2010. The variance in these raw data is much higher than we expected. In order to inspect for diel-scale fluctuations, we applied a three-hour moving window average to these data (line). This smoothing reduced but did not eliminate the fluctuations, which are in excess of 10 dB in this example.

The output of the PAR sensor was plotted on the same time scales to permit comparisons. In this example, there is some mild visual indication that smoothed echo intensity *might* be related to incident light intensity.

Another way to visualize the data is to plot the entire data set as a spectrum versus time. For the April data, this plot is shown in Figure 5. In this example, there are some instances of increased bottom echo intensities, particularly at the upper frequencies.

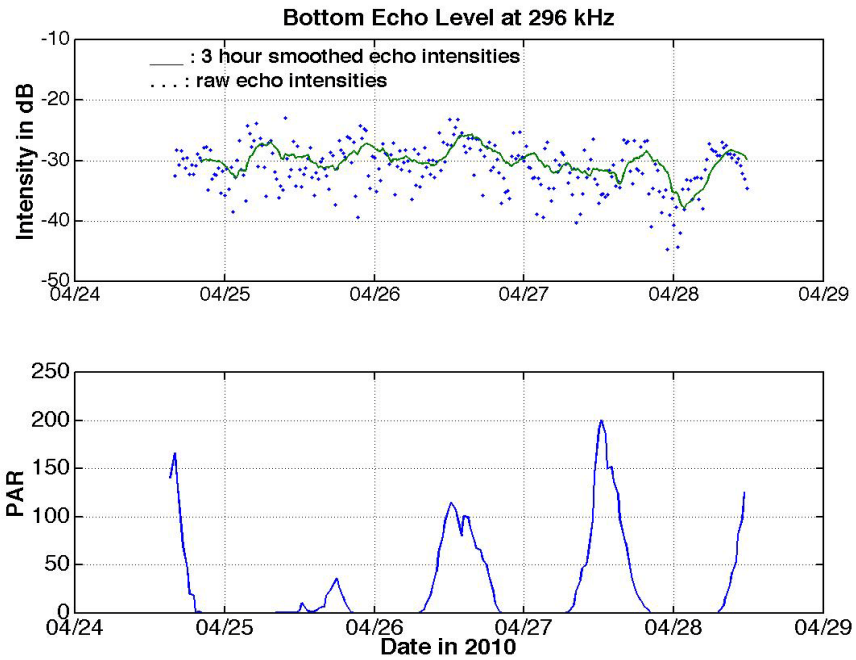

Figure 4. Plot of averaged bottom echo intensity (upper; dots) at 296 kHz versus time. A 3-hour moving window average of intensities is shown as a line. PAR data recorded at the same site are shown in the bottom plot.

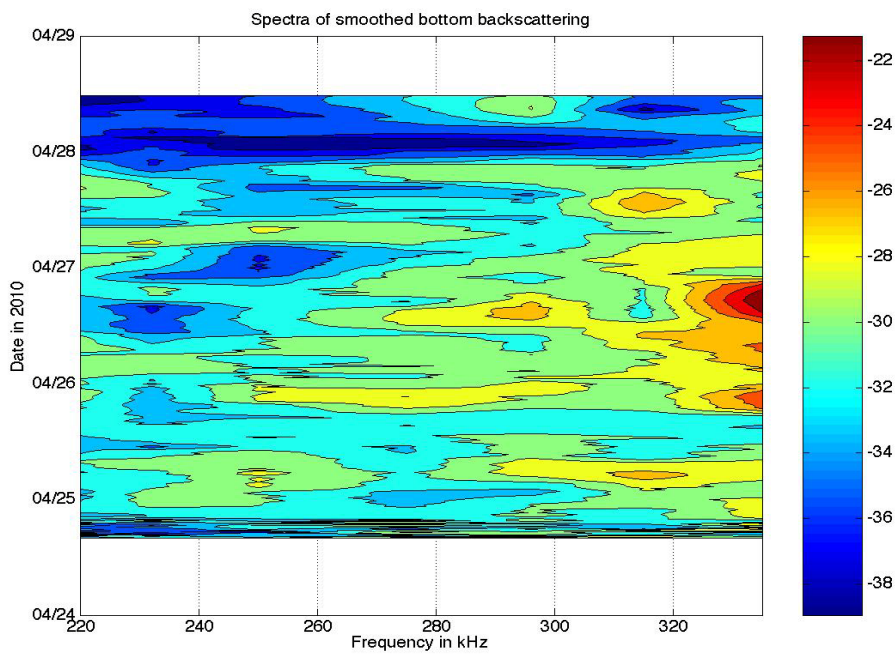

Figure 5. Bottom backscattering echo intensity versus frequency and time. Higher backscattering is shown in warm colors (reds) and lower backscattering shown in cool colors (blue). The color bar is scaled in dB.

We hypothesized that if increases in bottom backscattering were due to bubble production by benthic microalgae, we ought to be able to see a correlation between bottom echo intensities and some measure of incident light, such as PAR. One way to assess the relationship between PAR and bottom echo intensity is to measure the cross-covariance between these measurements. The light data was resampled at the acoustic data rate, and the two data sets compared in this way. Figure 6 shows the results for the 296 kHz data set from April. The cross-covariance is everywhere less than 0.5, indicating that there is no strong correlation between the fluctuations in these data. In other words, for this data set, the fluctuations in bottom echo intensities are not caused by incident light intensity -- or possibly that some other cause of fluctuations is much stronger.

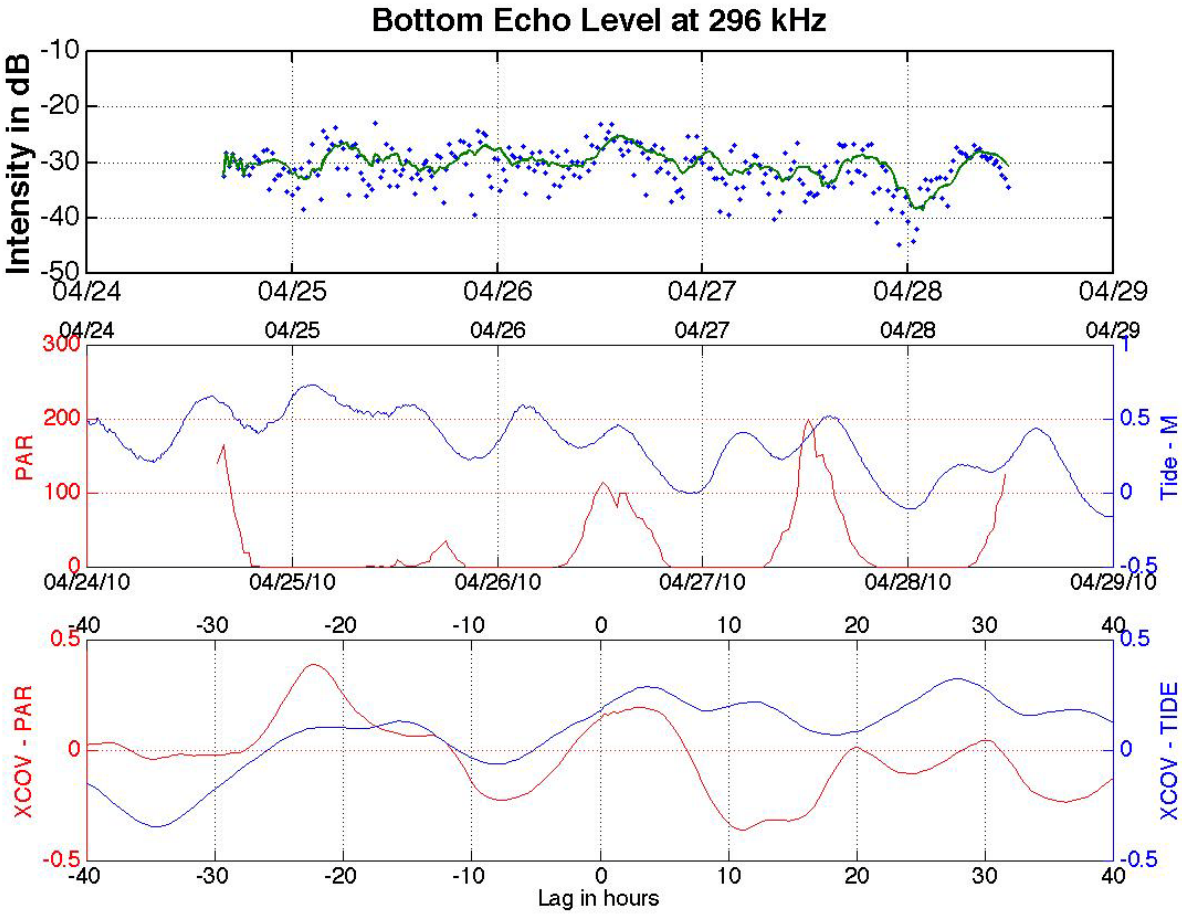

Figure 6. Plots of bottom echo intensity at 296 kHz (upper panel), PAR (red, middle panel), and tide (blue, middle panel) versus time along with the cross-covariance between smoothed echo intensity and PAR (red, lower panel) and tide (blue, lower panel) for the April 2010 deployment. Both individual echo data sets (dots) and 3-hour smoothed data (line) are shown. Levels of cross-covariance below 0.5 generally are considered evidence of lack of correlation between the variables.

Some indication as to the cause of this lack of correlation can be seen by comparing the auto-covariances of the PAR and bottom echo intensity data sets (Figure 7). In this data set, the auto-

covariance for PAR peaks at 0 lag, of course, and also at approximately 12 and 24 hour lags. The degree of correlation between days is slight, however. In the case of bottom echo intensity, the peaks are at odd, non-diel intervals and are even lower than those for PAR. In other words, the bottom echo intensities behave more or less as random values while fluctuating over a range of 10 dB or more.

Correlations with tide records produced similar results, with bottom echo levels largely uncorrelated with tides. Longer data records could possibly show different results, however.

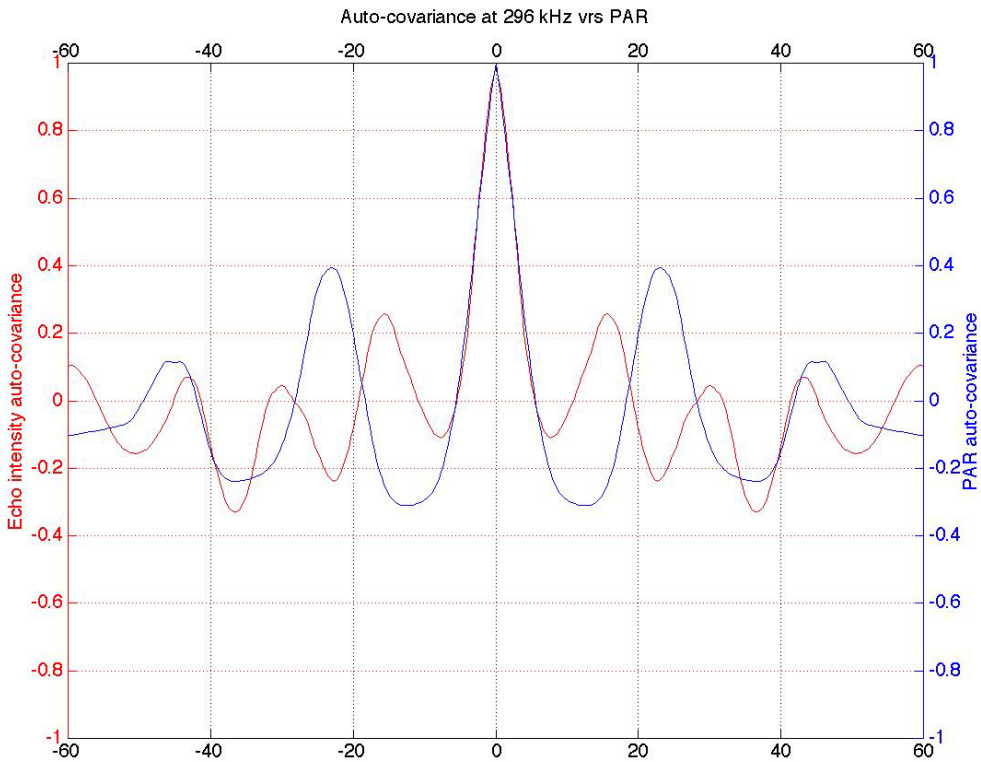

Figure 7. Plots of auto-covariance for bottom echo intensites (red) and PAR (blue) as a function of lag time in hours. One would normally expect strong peaks at 24-hour periods for diel signals such as PAR; in this case the correlation from day to day is weak, suggesting highly variable insolation. Similarly, the bottom echo intensities in this example do not show a strong diel pattern; the correlation from day to day appears essentially random.

A similar situation arose in June, where a somewhat longer data set was obtained. Figure 8 shows the cross-covariance of PAR and smoothed bottom echo intensities again having no discernible relationship. In this example, however, the variation of smoothed bottom echo intensity ranges to nearly 15 dB, but the behavior is not correlated with insolation.

Again, the auto-covariance plots (Figure 9) show that the bottom echo intensities do not correlate over diel periods, although the width of the main peak suggests the intensities are at least coherent over

periods of hours. The PAR data are highly correlated in this data set, as might be expected from the PAR data plotted in Figure 8.

Still, there was considerable day-to-day fluctuation in the bottom echo intensities, as shown in Figure 10. There are periods of coherent increases (and decreases) in the mean echo intensity that last for periods of up to two days, but they tend to occur at specific frequencies or pairs of frequencies and not, generally, at all frequencies at once. The magnitude of these short-term changes is 3-6 dB or more (keep in mind that a +3 dB change in echo intensity is a doubling of echo intensity) and, coupled with decreases of similar amounts at other frequencies, changes the scattering by up to 12 dB over the range of frequencies used here.

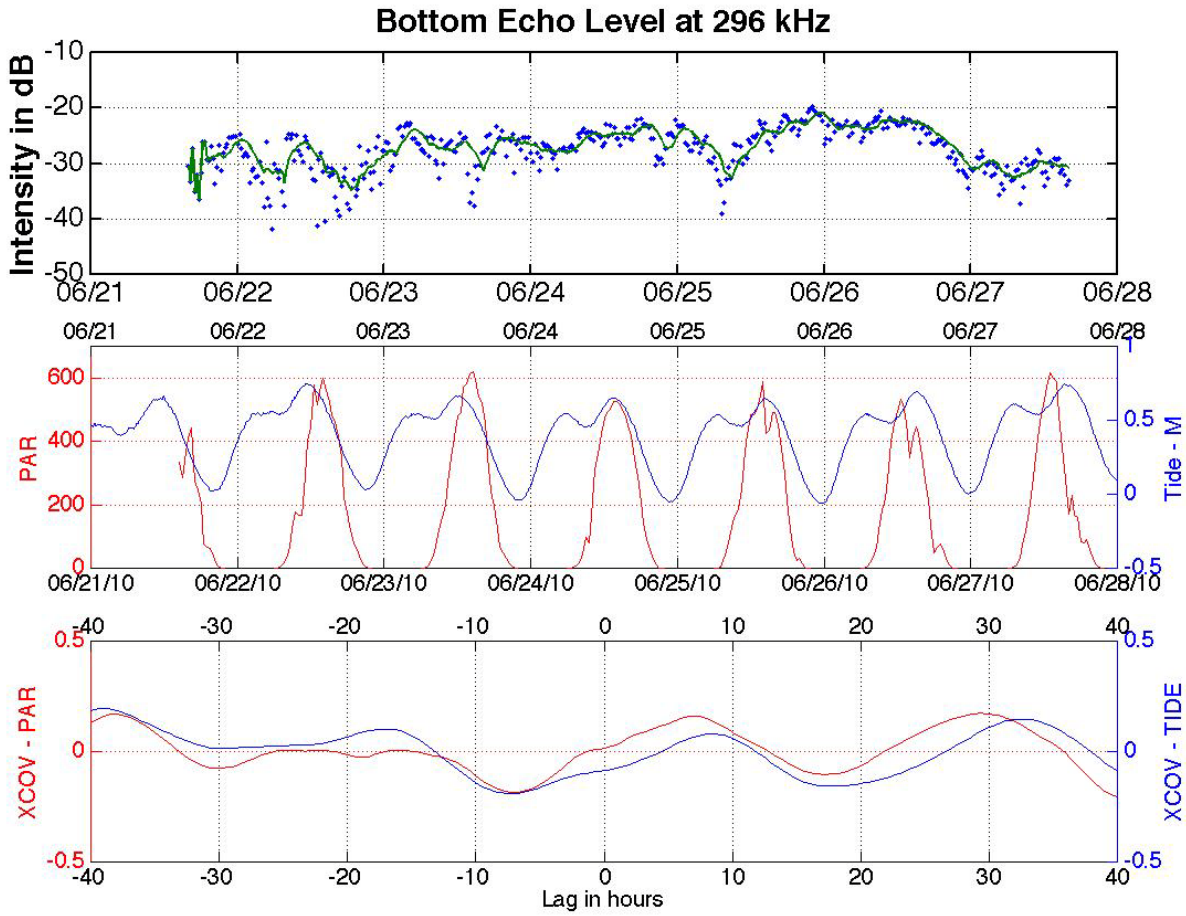

Figure 8. Plots of bottom echo intensity at 296 kHz (upper panel), PAR (red, middle panel), and tide (blue, middle panel) versus time along with the cross-covariance between smoothed echo intensity and PAR (red, lower panel) and tide (blue, lower panel) for the June 2010 deployment. Both individual echo data sets (dots) and 3-hour smoothed data (line) are shown. Levels of cross-covariance below 0.5 generally are considered evidence of lack of correlation between the variables.

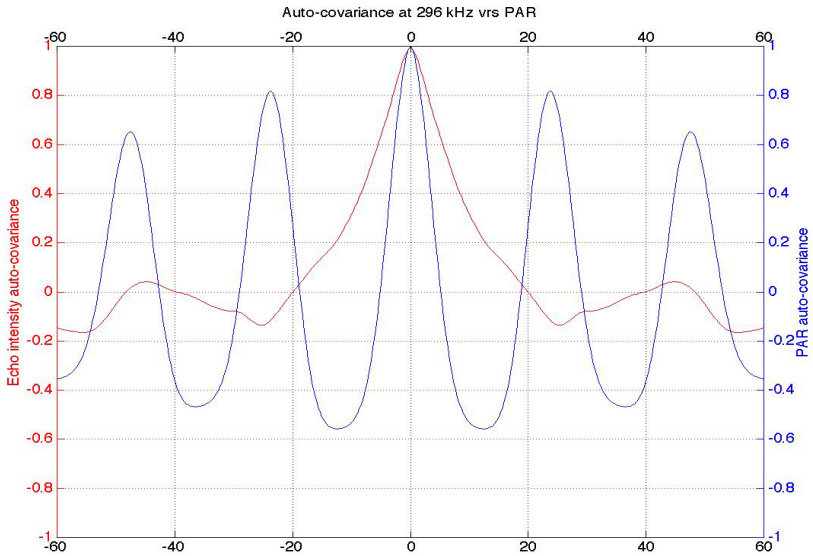

Figure 9. Plots of auto-covariance for bottom echo intensities (red) and PAR (blue) as a function of lag time in hours. This data set exhibits the strong diel (24 hour) correlation of daily insolation one would expect. The decrease in correlation over subsequent days of lag is partially due to the short length of the data series. The correlation of bottom echo intensity tapers off in a matter of hours and again shows no discernible correlation over diel periods.

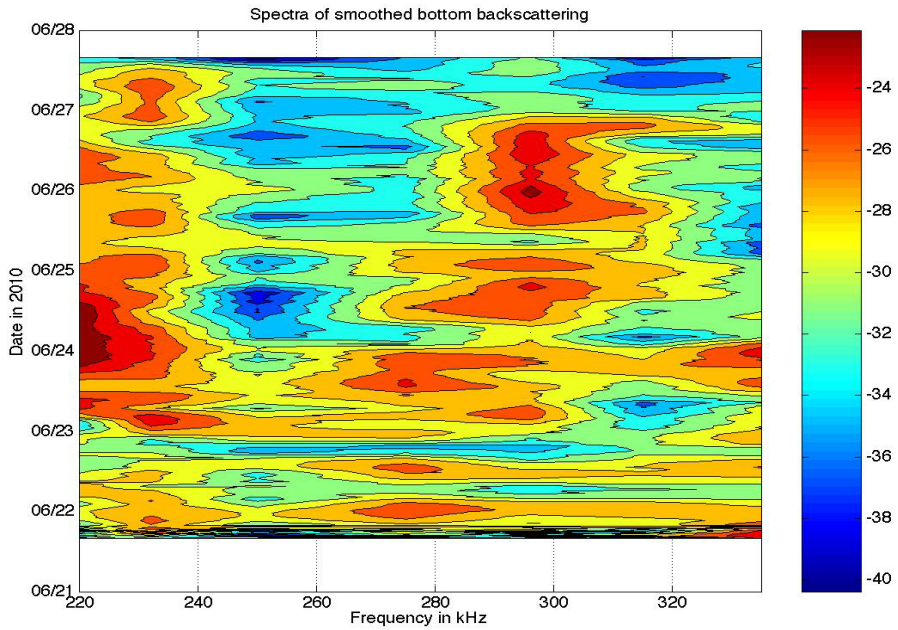

Figure 10. Bottom backscattering echo intensity vs frequency and time for the June, 2010 data set. Higher backscattering is shown in warm colors (reds) and lower backscattering in cool colors (blue)

Sand samples were collected at the deployment site on 28 June, 26 August, and 23 September (no samples were collected during the March or April deployments), and were qualitatively examined on the microscope. Sand from 28 June contained very few microalgae, thus it is likely that benthic photosynthesis was quite low, correlating with our SandScan data. Samples from 26 August and 23 September contained modest numbers of cells, mostly pennate diatoms. Some cells were loose, indicating that they had been living interstitially (Figure 11), whereas others were attached to the surface of sand grains (Figure 12). There were not enough cells to have formed algal mats. Whereas diatom mats have been previously observed at this site (David Thistle, personal communication), they have not been present during our SandScan deployments at this single site. It is in the nature of microalgae to vary in concentration with both the season, and with fluctuations in numerous environmental factors. Thus, we believe that a more rigorous testing strategy would be invaluable to refining our results. Also, the observations of supersaturated pore water at this site were made from mid September to mid November (Teasdale et al. 2004), so we might only now be coming into the season when benthic algae become abundant and bubble formation occurs.

Figure 11. Photomicrograph of a sand sample collected on 26 August 2010. Three pennate diatoms (indicated by arrows) are visible in the space between two sand grains. This sample was frozen when collected and thawed for visualization.

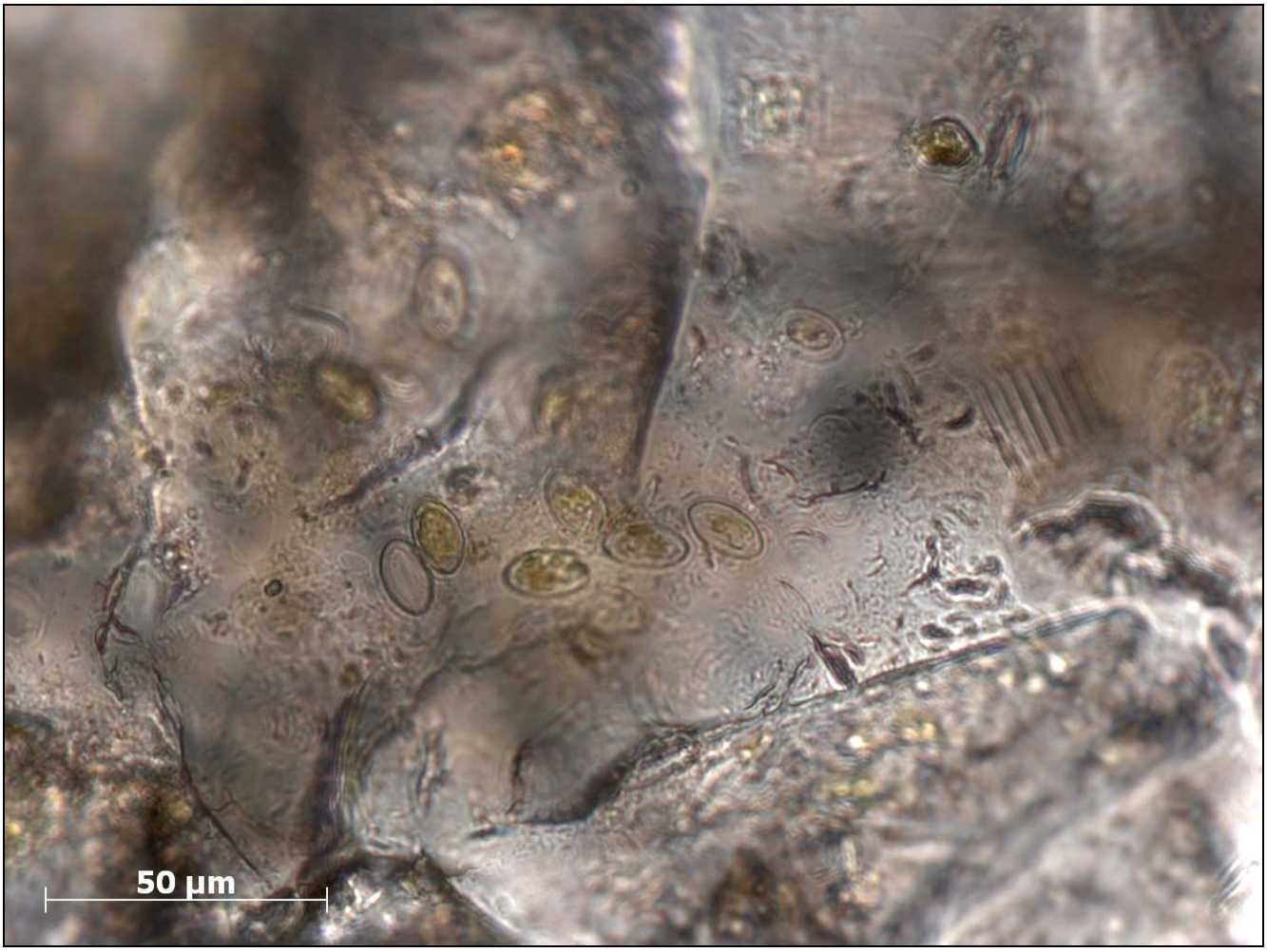

Figure 12. Photomicrograph of a sand sample collected on 26 August 2010. This is the surface of a single sand grain, and numerous small, elliptical pennate diatoms can be seen, attached to the surface of the grain.

The SandScan is deployed again as this report is written, during a time of year expected to be relatively calm (punctuated by occasional hurricanes) with even insolation. The SandCam, a commercial time-lapse camera developed for photographing birds, was deployed in a custom-made pressure case with SandScan in hopes of capturing some information on bottom topography. Another deployment is contemplated in late October or early November, roughly the end of the summer season at this location.

RESULTS

Significant short-term fluctuations in bottom backscattering have been observed at our test site, but the explanation for these data remains elusive. The length of the deployments, limited by hardware considerations in the current configuration, may be too short to allow us to detect the mechanisms at work if they are physical, while deployment problems with the time-lapse camera (which we think we have now mastered) have precluded us from evaluating the effects of benthic megafauna. Seasonal fluctuation in the concentration of benthic microalgae (and thus the amount of photosynthesis and oxygen production) is likely to also have contributed to our results to date.

IMPACT/APPLICATIONS

The answers to the questions we are addressing have implications for understanding:

1) the stimuli cuing emergence,
2) the role of bubbles in scouring surficial sediments,
3) the performance of naval sensors used to detect objects on, in, or near the seabed,
4) the characteristics of acoustic communications channels in shallow water,
5) the development of mathematical models for seafloor sound scattering,
6) and, the limitations and benefits of acoustic methods now being proposed and used for classifying, describing, and mapping benthic habitats in the littoral zones of many coastal nations.

RELATED PROJECTS

Markus Huettel, one of David Thistle's colleagues at Florida State University, has been funded by ONR to study bubbles in near-shore, sandy sediments. In one subproject, he will investigate their distribution along transects in the sub-littoral. We had originally planned to deploy our gear near one of Dr. Huettel's sites in order to independently test the relationship between the acoustic properties of the sediment and the variables he is measuring. The presence of significant amounts of shell hash at those study sites has caused us to change our approach. Should one of the oxygen probes, made of glass, encounter a shell as it is forced into the bottom, it would be broken. Our revised plan is to work at a 5-m site where David Thistle has done oxygen sensor work previously. That site is relatively free of shell fragments. We now plan to supply Dr Huettel with cores from the Thistle site. They will become part of his project, broadening his work in time and space and providing us with additional information about our study site.

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