# Beach nourishment activities and their potential impacts on sediment movement and biological resources around critical hard-bottom habitats on the shoreface of the Grand Strand, SC

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## 1. Introduction

The Grand Strand hosts the only significant aggregation of nearshore hard-bottom habitats in South Carolina. These habitats are of particular importance on the South Carolina continental shelf as they provide the framework for highly productive benthic communities (eg. Wenner et al 1983). Offshore, where they have been more thoroughly studied, these marine hard-bottom areas provide attachment substrate, predator refugia and foraging grounds for a wide range of invertebrates and fish, including many important fishery species (Grimes et al 1982; Wenner et al 1983; Sedberry and Van Dolah 1984). Little is known about the biocomplexity of these critical hard-bottom habitats nearer shore, including the spatial and temporal variability and interactions between the geological, physical, and biological processes. Further, the consequences of continued beach nourishment for the complex interactions between the physical and geological processes and biological communities remain poorly understood.

The focus of our study was the shoreface and inner shelf of the Grand Strand region, located offshore of northeastern South Carolina in Long Bay (Fig. 1). The Grand Strand is centered on a 54 kilometer-long arcuate strand that has few significant tidal inlets and with little fluvial input of "new sediment" to the coastal system. Resistant Cretaceous and Tertiary strata outcrop on the shoreface throughout the Myrtle Beach section, producing hard-bottom substrates and rocky ledges with a meter or more of vertical relief. Seaward, the inner continental shelf is low relief and largely sediment limited, covered by a patchy and discontinuous sand sheet. Without contribution from fluvial sediment sources, the outcropping hard-bottoms and the mainland beaches and barriers become the main source of sediment for the Long Bay sediment budget (Gayes, et al., 2003). In addition, beach fill from the Myrtle Beach re-nourishment project may be an additional source of sediment to the shoreface and inner-shelf regions.

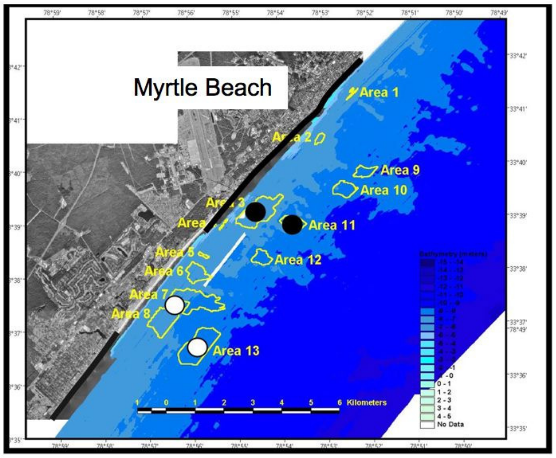


***Figure 1**. Index reef areas on the Grand Strand. These same locations are shown superimposed on the regional SC Coastal Erosion Study regional side scan sonar mosaic. Black circles indicate the study areas for the project, which were slightly south of 2<sup>nd</sup> Ave. pier in downtown Myrtle Beach. The black lines along the beach indicate the segments of Myrtle Beach that will be re-nourished.*

Previous studies indicate that sediment is not accumulating on these hard-bottom surfaces; instead, sediments appear to migrate rapidly across hard-bottom areas (Ojeda, Gayes, and Sapp, 2001). Sediment movement across living hard-bottoms can affect ecological communities through several mechanisms. Sedimentation has been shown to decrease the growth rates, densities and recruitment success of many sessile invertebrates such as corals, sponges and ascidians and in more extreme cases completely smother living reef habitats (Hunt and Wittenberg 1992; Miller et al 2002; Golbuu et al 2003; Fabricius 2005; Dikou and Woesik 2006). In an observational study on hard-bottom reefs in North Carolina, Renaud et al., 1997 reported that changes in sediment thickness and distribution on hard-bottom surfaces had profound effects on the entire ecological communities that these hard-bottoms support. Defining the sediment transport pathways that cover and uncover these hard-bottom habitats on the shoreface and inner-shelf is vital to understanding the effects these mobile sand bodies have on proximal living reef habitats. Moreover, understanding the natural processes are further complicated when beach nourishment practices result in adding millions of cubic yards of sediment along the beach and shoreface. As beach fill is transported across the shoreface and migrates seaward toward the hard-bottoms, substrate burial and/or sand scour can negatively impact communities of sessile invertebrates that are key to the proper functioning of these habitats. A previous sediment transport study conducted offshore of Myrtle Beach indicates that the inner-shelf is an active region, with shear stresses frequently exceeding the critical stress for sediment mobilization during common frontal passages and small to moderate storm events (Sullivan et al., 2006). In addition, studies to assess large-scale changes in hard-bottom habitat area following the initial Myrtle Beach Nourishment Project in 1999 indicated that most reef areas exhibited a modest change (Ojeda, Gayes, and Sapp, 2001). The greatest changes in hard-bottom habitat area occurred at the sites closest to the beach construction where a small net loss of habitat was measured. This suggests that benthic reef communities in closer proximity to a nourished beach are more likely to be impacted both by natural causes and by the movement of renourishment sand from the adjacent beach.

In order to understand the complex interactions between the geophysical environment and habitat structuring of sessile invertebrate communities on marine hard bottoms, a multi-disciplinary approach consisting of *in-situ* measurements and observations was undertaken. This was accomplished through long-term direct measurements and 1-D modeling of sediment transport, deposition, and erosion on the hard-bottom habitats coupled with (1) geophysical surveys examining rates of change in the amount of hard-bottom habitat, (2) examination of the sessile invertebrate community structure on the natural hard-bottom habitats and (3) recruitment of invertebrates at various proximities to the seafloor using stacked arrays of artificial recruitment substrates to examine the linkages between sediment movement and recruitment dynamics as a function of distance from the seafloor.

## 2. Objectives

We hypothesized that changes in sediment distribution occur on short time scales of days to months on these hard-bottom reef surfaces, and thus will effect recruitment and community structure on these shorter times scales in addition to seasonal and longer temporal scales. Furthermore, we hypothesized that the hard-bottom habitats on the shoreface and inner-shelf will be significantly impacted from the re-nourishment project on these shorter times scales of days to months. In order to test these hypotheses, we designed a study with the following objectives.

1. Quantify the magnitude, frequency, and direction of sediment transport on and around the nearshore hard-bottom habitats of the Grand Strand
2. Determine if the hard-bottom habitats on the shoreface and inner-shelf are significantly impacted from the re-nourishment project on the shorter times scales of days to months due to increased sediment supply and net offshore transport
3. Determine what effect this may have on longer-term changes in community structure and shorter-term recruitment dynamics.

## 3. Methods

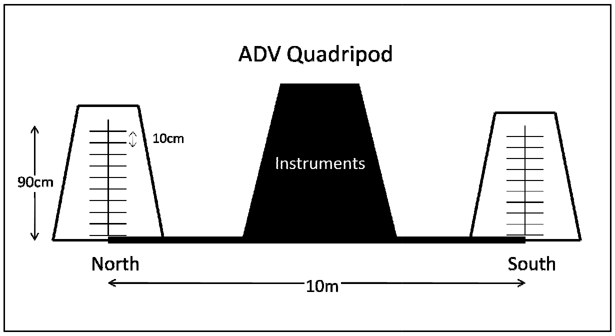
Due to a successful NSF Major Research Instrumentaion (MRI) grant, the instrumentation deployed to collect measuremets of sediment transport was significantly increased. Data collected at the "inshore site", located approximately 850m offshore, include high-resolution current velocity profiles and suspended sediment concentration profiles within the bottom boundary layer.Directional wave spectra and wave characteristics have also been collected at this site. Data collected at the "offshore" site, located approximately 2.5 km offshore of Myrtle Beach, includes current velocity profiles throughout the upper water column, directional wave spectra, seabed elevation, and near-bed wave and current 15 cmab.from July 2008 - December 2009. Two instrument sites were established at the index reef sites at Areas 3 and 11 located 850 and 2.5 km offshore of Myrtle Beach, respectively (Fig. 1). Throughout 17 months of the study in-situ measurements of sediment transport magnitude, direction, and frequency were collected within the bottom boundary layer (BBL) at the 2 study sites. At the “inshore site”, approximately 850 meters offshore of Myrtle Beach, a high-resolution downward-facing 1200 kHz RD Instruments Acoustic Doppler Current Profiler (ADCP) measured current velocities in 10 cm “bins” throughout the lower 1.3 meters above the seabed. Wave bottom velocities and mean current profiles were obtained over a 17 minute burst every 2 hours. Additionally, an Acoustic Backscatter Sensor (ABS) was mounted at the same elevation above the seabed which collected suspended sediment profiles in the BBL and seabed elevation changes. An upward-looking 1500 kHz Nortek Acoustic Wave and Current profiler (AWAC) was also deployed to measure surface directional wave spectra. Sediment transport magnitude was calculated as the product of the time series of current velocity profiles and suspended sediment concentration profiles that were collected within the lowest 1.3 meters above the seabed. The Instrumentation at the “offshore” site, approximately 2.5 km offshore, included an upward-looking 1200 kHz RD Instruments ADCP that measured directional wave spectra and current velocity profiles throughout the upper-water column. In addition, a Sontek Acoustic Doppler Velocimeter (ADV) measured high resolution current velocities at approximately 15cmab (elevation changed as sediment was eroded or deposited) and served as an altimeter, measuring changes in seabed elevation. The ADV sampled at 1 Hz for 17 minutes every 2 hours, and from these data the current velocities due to tides and wind-driven forcing, as well as the wave orbital velocities within the BBL, were obtained. The time series of the mean current velocities and measured wave orbital velocities were input into a 1-D bottom boundary layer (Styles and Glenn, 2000) to calculate vertical profiles of current velocity, suspended sediment concentrations, and suspended sediment transport profiles within the bottom boundary layer in order to quantify the sediment transport at this site. In addition, the 1-D model was used to calculate the time series of bottom shear stresses due to wave-current interactions at both study sites.

By using these aforementioned methods at each site, the sediment transport magnitude, frequency, and direction on the hard-bottom reefs were quantified from July 1, 2008 – December 2009 over temporal scales ranging from storm events to seasons. Additionally, the frequency and type of meteorological events that resulted in sediment transport at the two sites were identified in the time series data and also categorized using wind velocity data reported at Springmaid Pier and NOAA's daily weather maps. The along-shelf and across-shelf transport magnitude during the different types of meteorological events were quantified and the net direction of transport over the event scale and seasonal scales were also quantified.

In order to observe spatial changes in sediment cover over time scales of 6-8 weeks, side-scan sonar surveys conducted around the two reefs areas. The changes in bottom substrate, i.e, sediment cover, on and around the hard bottom habitats were determined through a comparison analysis of subsequent geophysical surveys.

*Methods – Vertical Recruitment Arrays*

For the recruitment portion of the study, vertical arrays consisting of ten 15 x 15cm² unglazed slate tiles were constructed (following Harriot and Fisk 1987). Tiles were stacked on a threaded rod with 10cm PVC spacers between each tile for a total height of approximately 90cm (Figure 2). Stacks were affixed by SCUBA divers to metal A-frames located 5m to the north and south of each ADV/ADCP quadrapod (inshore and offshore, see Figure 1 for site description), with each stack oriented perpendicular to the seafloor and recruitment surfaces parallel to the seafloor. Collection and deployment of tiles took place during retrieval/deployment of instruments at the ADV sites, approximately every 6-8 weeks between November 2008 and December 2009.



*ployed on either side*
*t to scale.*

Collected tiles were fixed with a 10% buffered formalin/seawater solution in the field, placed into individual labeled cloth bags, and later transferred to 70% isopropyl in the lab. Percent cover estimates of sessile fauna that recruited to the upper and lower surfaces of each tile were determined using a point-quadrat technique modified from Sutherland and Karlson 1977. A clear acrylic frame with 100 grid points (formed by the intersections of 10 x 10 interwoven monofilament lines) was placed over a tile submerged in a tray of fresh water under a dissecting microscope. Sessile organisms under each point were marked as present/absent and identified to the lowest practical taxonomic affinity by a trained taxonomist. Taxa with "canopies" or vertical growth profiles (primarily hydroids, bryozoans, and octocorals) were counted towards percent cover only if the basal area of attachment occupied a point. In the instance of multiple species occurring under a single point, all species were recorded. Taxa not considered representative of the sessile invertebrate community (motile organisms, algae, evidence of predation, remnants of once-living organisms such as empty shells, barnacle scars, etc) were recorded but not counted towards percent cover, with the exception of amphipod and polychaete tubes. Tube-dwelling organisms frequently evacuate tubes during the collection and fixation processes, and not counting them could result in an underestimation of percent cover. Thus, any empty tube (distinguishable as belonging to either an amphipod or polychaete) encountered under a point was considered to contain an animal.

*Statistical Analyses*

Recruitment responses included "total living cover" (the sum of all points for all taxa; possible to have >100% cover on a tile surface if multiple species were present under a given point), "total surface cover" (sum of all points with at least one taxon; maximum value of 100%), and "surface cover" for each of several broad taxonomic groupings. Data for all measures were arc-sin transformed (with the exception of "total living cover," since cover could exceed 100%, thus producing undefined arc-sin values) to meet the assumptions of parametric analyses.

Weighted analysis of variance (ANOVA; $\alpha=0.05$) was used to compare recruitment between inshore and offshore sites ("site"), six deployment periods ("time"), and position of tiles on a stack ("height"). Tile tops and bottoms were not statistically compared due to differing surface textures (bottoms had ridges while tops were smooth), so results are presented separately for each surface type. North and south stacks were not nested within site in this model; instead, within each site and time, tiles of the same height were averaged across stacks to reduce the effects of within-site variability. Pair-wise comparisons of sites, times and heights were performed using Tukey's multiple comparisons test. All statistical analyses were performed using Minitab 16.

## 4.0 Results

Seasonal differences in the magnitude, direction, and frequency of transport were observed due to the different types of meteorological events that occurred during the seasons (Table 1). Throughout the summer through early November, tropical cyclones and dominant high pressure systems (DH) were the dominant type of meteorological systems that impacted the study site. Dominant high pressure systems result from a large-scale high pressure system over New England or the interior northern U.S. resulting in northerly to northeasterly winds along the South Carolina coast. These type of events transported sediment towards the southwest, in the along-shelf direction, with a smaller offshore component. Throughout the summer months, a total of 2.28 kg m$^{-1}$ of suspended sediment was transported in the along-shelf direction, towards the southwest, and 0.616 kg m$^{-1}$ was transported in the offshore direction (Table 1). The frequency of sediment re-suspension and transport was the least during the summer. In October and the first week in November, three dominant high pressure systems (DH) occurred with a frequency of 1-2 weeks. The dominant high systems resulted in a total of 17.50 kg m of sediment being transported in the along-shelf direction, towards the southwest, with a smaller offshore component of 4.20 kg m$^{-1}$. However, the dominant high pressure systems gave way to commonly occurring mid-latitude cyclones around mid-November. At this time the large scale atmospheric conditions began to shift, and mid-latitude cyclones (MLC) and their associated frontal systems became the driving force for sediment transport. As MLCs moved across the region, the preceding warm fronts resulted in strong winds from the southeast and southwest ranging from 10 – 15 m s$^{-1}$. Following the warm front, the trailing cold front would pass over the site resulting in relatively calm winds from the northwest. These warm front events resulted in sediment transport towards the northeast, and slightly onshore.

| **Event date** | **Event type** | **Peak $U_b$ (cm/s)** | **Peak $U_{15}$ (cm/s)** | **Max shear velocity (cm/s)** | **Sediment transport magnitude (g/cm/s)** | **Compass direction** | |
|---|---|---|---|---|---|---|---|
| 7/18 - 7/19 | TD #3 | 23 | 7 | 3.88 | 0.5 | 258 | WSW |
| 8/20 - 8/23 | TS Fay | 30 | 5 | 7.98 | 1.3 | 207 | SSW |
| 9/4 - 9/7 | TS Hanna | 60 | 6 | 25.3 | 806 | 194 | SSW |
| 10/11 - 10/13 | DH | 29 | 10 | 5.84 | 6.4 | 215 | SW |
| 10/24-10/26 | DH / ETs | 32/43 | 4/5 | 6.67 / 12.19 | 12 | 210 | SW |
| 11/3 -11/4 | DH | 22 | 13 | 3.62 | 0.057 | 201 | SSW |
| 11/13 - 11/15 | ETs / ETw | 24/25 | 1.5/5 | 4.27 / 4.65 | 0.95 | 36 | NE |
| 12/9 -12/12 | DH / ETclo | 22/28 | 10 | 3.37 / 5.77 | 12 | 46 | NE |
| 1/6 - 1/8 | ETw | 27 | 5 | 5.5 | 4.4 | 27 | NNE |
| 3/12-3/14 | DH | 26 | 6 | 5.25 | 0.56 | 206 | SSW |
| 3/26 - 3/29 | DH / ETw | 25 | 5 | 3.52 / 4.84 | 5.2 | 208 | SSW |
| 4/14 | ETw | 38 | 12 | 9.34 | 158 | 28 | NNE |
| 4/20 - 4/21 | ETw | 25 | 15 | 4.51 | 5.2 | 39 | NE |
| 5/13 – 5/14 | DH | 27 | 5.6 | 5.1 | 3.2 | 233 | SW |
| 5/19 – 5/22 | DH | 25 | 10 | 5.3 | 2.8 | 245 | WSW |
| 7/23 – 7/24 | ETw | 23 | 8.7 | 4.9 | 0.8 | 2 | N |
| 10/24 | ETw | 22 | 2 | 4.5 | 0.1 | 296 | WNW |
| 11/10– 11/11 | T.S. Ida | 25 | 18.7 | 5.3 | 18.7 | 201 | SSW |

Therefore, the net direction of the transport over a year was determined by the number of the warm fronts compared to dominant high pressure events, as these events all had the same order of magnitude of suspended sediment transport (Table 1). However, during the hurricane season of 2008 two tropical storms impacted the study site. Tropical Storms Fay and Hannah both resulted in transport towards the southwest and offshore, which was in the same direction as the transport during the autumn and spring seasons when common DH systems with northeasterly winds occurred. This additional transport due to the tropical systems resulted in the net transport direction over the study period being towards the southwest and offshore; however, when tropical systems were not included in the cumulative transport direction the net direction was towards the northeast and onshore at the site. This indicates that the net transport direction could easily be in the opposing direction during a given year, and that throughout annual cycle sediment is oscillating back and forth along the shelf. The tropical cyclone activity plays a larger role in determining the net direction of transport from year to year.

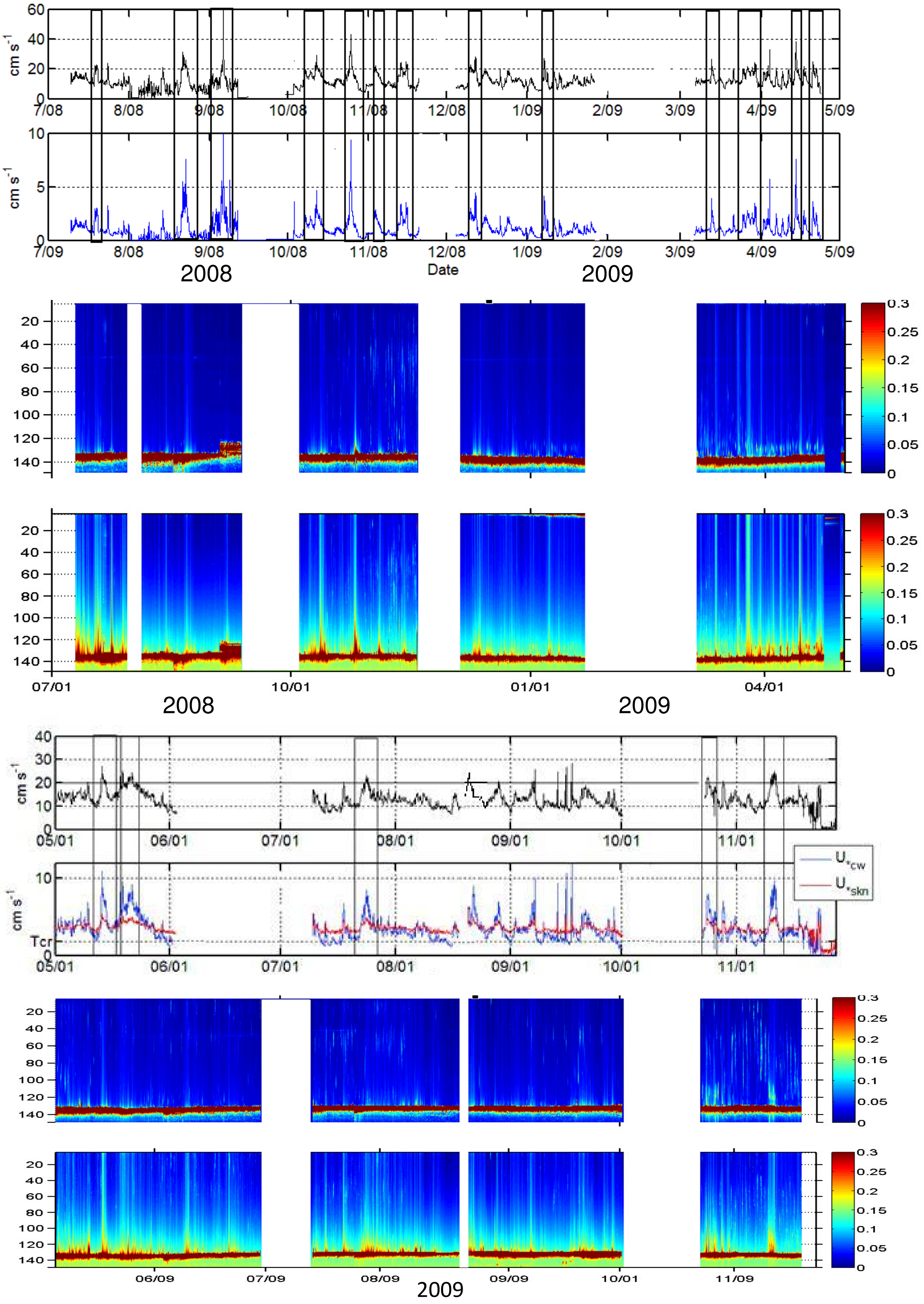


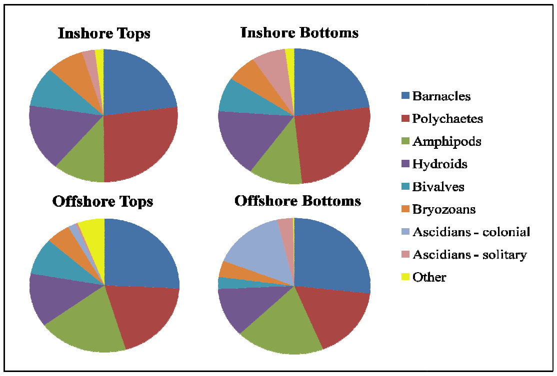
***Figure 3****: Time series of root-mean-squared bottom wave velocities and bed shear stresses from the offshore site shown with the suspended sediment concentration profile data from the Acoustic Backscatter Sensor at the inshore site. Data show that the suspended sediment concentrations increased during each of the identified sediment transport events Table 1, and that the model and the measurements are in agreement. The top ABS time series shows course sand resuspension, and the bottom ABS time series shows the fine sand sediment resuspension.*

The seabed elevation data at both sites (not shown) indicated that sediment thickness changed frequently (1 – 3 weeks) on the hardbottom surfaces throughout the year, with the most active months during the autumn and spring months. Sediment elevation changes were on the order of 1 – 5cm in most cases during high energy events, with erosion occurring during high wind driven wave and current velocities when sediments were suspended vertically in the water column. As the winds and wave conditions waned, sediment thickness increased slightly due to the settling of suspended sediments. Net erosion of 1 – 2cm was common during most of the events throughout the year. However, in between events during "fair-weather", it appeared that asymmetric waves were responsible for moving sediment onto the hardbottom and increasing the seabed elevation and sediment thickness. This occurred mainly in the summertime when the frequency of events was the lowest and fair-weather swells were dominant. This new sediment was easily suspended when a frontal system or DH pressure system occurred, as sediments on hardbottoms are easily resuspended due to the turbulence created by the roughness of the underlying substrate. These areas are most likely to be where sediments are first re-suspended when wave velocities increase, and where sediments are the last to settle out after a sediment transport event. Hence, this is one reason why we did not see increased sediment supply and burial on the hardbottom surfaces.

Side scan sonar surveys were conducted throughout the study period approximately every 4 - 8 weeks around the hardbottoms areas to assess changes in sediment cover and substrate. In addition, a habitat classification alogorithm was used to determine the percent cover of sand versus hardbottom and to identify areas of change in substrate and habitat between surveys. The geophysical surveys confirm that the hardbottom surfaces are active places for sediment movement. The resuts indicate that there was no large-scale net change in the amount of sediment within the study region. The surveys corraborate the results form the sediment concentration and seabed elevation data indicating that there is a thin veneer of sediment that appears to be mobile over these hardbottom areas.

## *Recruitment results*

A total of 37 sessile invertebrate taxa were found on the vertical settlement arrays collected between January 2009 and December 2009 (see full list in Appendix A). The dominant taxonomic groups in the 438 analyzed collections are presented in Figure 4. The general structure of the epifaunal assemblages was dominated by barnacles, which occurred in 77% of collections. Dominant barnacles included *Balanus venustus* (also the most frequently occurring species overall, present in 63% of collections), *Balanus improvisus* (27% of collections), and *Balanus trigonus* (14% of collections). Also dominant were polychaetes (68% collections), specifically the tube-building families Serpulidae (49% of collections), Sabellariidae (44% of collections), and Sabellidae (12% of collections). Tubiculous amphipods, including *Ericthonius* sp. and *Corophium* sp., were present in 48% of collections. Hydroids were present in 44% of collections, with *Bougainvillia* sp. (25% of collections) and *Obelia* sp. (16% of collections) as the dominant taxa.



Percent cover on settlement tiles varied greatly, ranging from 0% to over 200% total living cover on a single surface. On the top surfaces of tiles, there was no significant difference in the amount of total living cover or total surface cover between sampling sites (Table 1). On tile bottoms, the offshore site had significantly greater living cover, although there was no significant difference in total surface cover.

*f broad*
*re separated*
*/bottom).*

Unlike total percent cover, the percent cover of individual taxonomic groups was strongly influenced by site. Polychaetes, hydroids, bivalves, and solitary ascidians had significantly higher mean percent cover at the inshore site, and barnacles and amphipods had significantly higher mean cover at the offshore site for both tile tops and bottoms (Table 1). Mean percent cover of colonial ascidians was significantly higher at the offshore site for tile bottoms only.

Deployment period was highly significant for total living cover and total surface cover on both tile surfaces (Table 2). Mean percent cover for both measures was significantly lower on tiles deployed during the winter and spring (Nov-Jan and Mar-Apr) than for all other periods, and exhibited an increasing trend throughout the year, with greatest mean values for both

|  |  | Total Living Cover (can exceed 100%) | Total Surface Cover (maximum 100%) | Barnacles | Polychaetes | Amphipods | Hydroids | Bivalves | Bryozoans | Ascidians - colonial | Ascidians - solitary |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | df | p | p | p | p | p | p | p | p | p | p |
| *Tile Tops* |  |  |  |  |  |  |  |  |  |  |  |
| Site | 1 | 0.418 | 0.354 | 0.048 | 0.000 | 0.000 | 0.000 | 0.000 | 0.126 | not run | 0.000 |
| Time | 5 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | not run | 0.000 |
| Height | 9 | 0.000 | 0.000 | 0.000 | 0.027 | 0.043 | 0.000 | 0.105 | 0.426 | not run | 0.536 |
| Error | 90 |  |  |  |  |  |  |  |  |  |  |
| *Tile Bottoms* |  |  |  |  |  |  |  |  |  |  |  |
| Site | 1 | 0.032 | 0.746 | 0.028 | 0.000 | 0.000 | 0.000 | 0.001 | 0.093 | 0.000 | 0.000 |
| Time | 5 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.024 | 0.000 | 0.000 |
| Height | 9 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.309 | 0.112 | 0.012 | 0.607 |
| Error | 88 |  |  |  |  |  |  |  |  |  |  |

***Table 2:*** *Results of repeated measures ANOVA comparing percent cover of epifaunal invertebrates on top and bottom tile surfaces between inshore and offshore sites (site), deployment periods (time), and tile positions (height).*

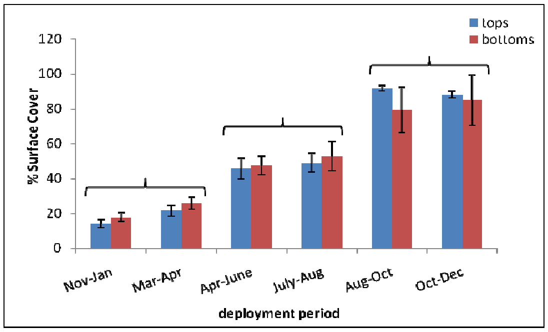


***Figure 5.*** *Mean percent total surface cover by deployment period (inshore and offshore sites combined). Error bars represent 1 SE; brackets indicate sets of deployment periods that were significantly different from other sets.*

measures occurring during the late summer and early fall deployments (Aug-Oct and Oct-Dec, respectively; Figure 5). Deployment period was also highly significant for all taxa groups on both top and bottom tile surfaces (Figure 6). Most groups followed the general pattern of significantly lower mean percent cover in the winter months followed by increasing cover throughout the year; however, there were a few notable exceptions. At the inshore site, barnacle cover declined dramatically on tile tops and bottoms deployed from Apr-June; interestingly, percent cover of barnacle scars and dead barnacles at the inshore site was also highest during this period. This may be an indication that other biological or physical factors, as opposed to a decrease in larval availability, were responsible for the observed decline in barnacle survivorship. Polychaetes, which were consistently higher at the inshore site during every deployment period, decreased drastically at the inshore site and all but disappeared from the offshore site during the final deployment. Tube-dwelling amphipods, which had greater mean cover at the offshore site for every deployment period, displayed the opposite pattern, recruiting heavily during late fall/ winter/early spring and decreasing during the warmer months, with peak cover occurring during the final deployment.

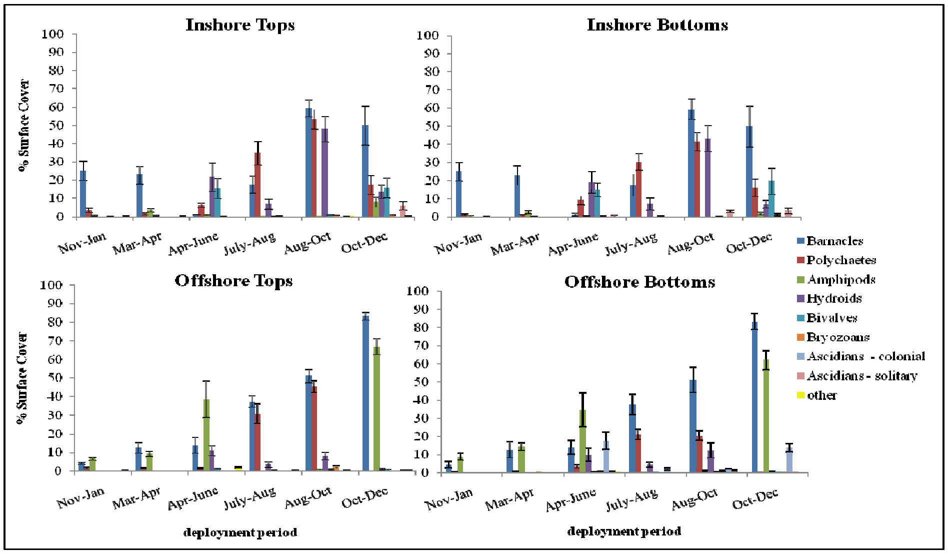


***Figure 6.*** *Mean percent surface cover by deployment period and site for broad taxonomic groupings. Error bars represent 1 SE.*

Tile height was another important factor affecting recruitment on both top and bottom surfaces. Mean living cover and surface cover were significantly higher towards the middle portion of a stack (positions 3-7), and significantly lower at the highest position on a stack (tile 10; Figure 7). Mean cover also tended to be low near the bottom of a stack, although not enough for the difference to be significant. Of the taxonomic groups examined, significant results for height on at least one tile surface were found for barnacles, polychaetes, amphipods, hydroids, bivalves, and colonial ascidians. Barnacles, amphipods, and colonial ascidians followed the general overall pattern of low cover at the top and bottom of a stack and high cover in the middle, for both tile surfaces. Bivalve and polychaete cover was lowest at the bottom of a stack rather than the top; other exceptions included hydroids, which showed an increasing trend in cover from the top to the bottom of a stack for both tile surfaces.

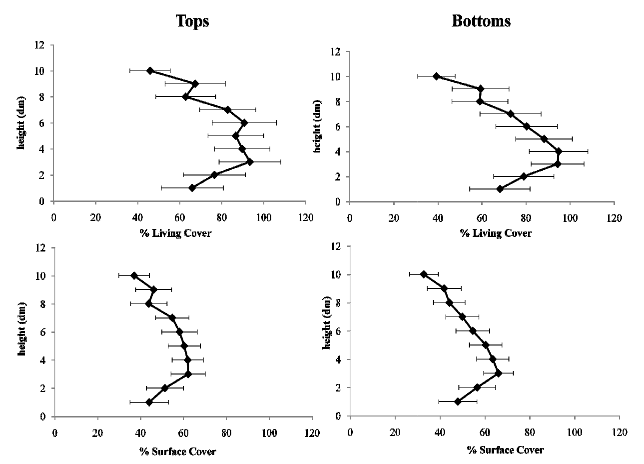
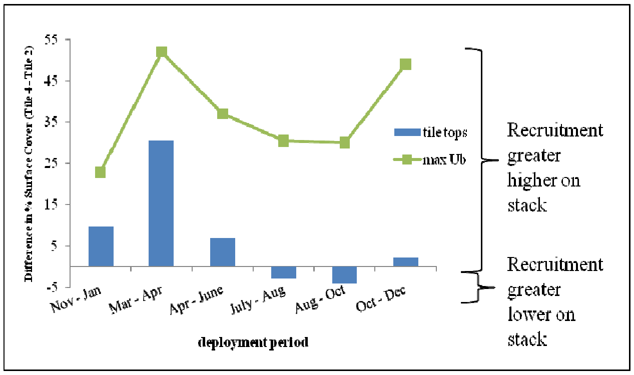


*Figure 7. Mean percent living and surface cover by tile position for top and bottom tile surfaces. Site-height interactions were never significant for total cover measures; therefore, values are averages of data from inshore and offshore sites.*

## 5.0 Discussion

Physical data recorded at different elevations from the sea floor were used to interpret vertical recruitment patterns on the tile stacks. Burial of tiles may have been a factor in the low percent cover observed on tile 1. According to the Range-to-bottom (RTB) data provided by the ABS at both sampling sites, the tile at the bottom of the stack was frequently covered and uncovered as sediment transport over the hard-bottom caused the fluctuation of seabed elevation. Sediment accretion of at least 1cm occurred once or more during every deployment period and may have been detrimental to the recruitment and survival of organisms that settled on the bottom tile, especially those with low/encrusting growth forms. For instance, the success of hydroids on tiles 1-3 may have been attributed to their vertical growth profile, which could prevent them from being smothered by sedimentation.

In addition to periods of burial, which were usually short-term and episodic, other aspects of sediment movement may have been important in determining recruitment patterns. Wave and current data from the ADV/ADCP indicated that a slight difference in depth between the two sampling sites (7m inshore, 10m offshore) may have been responsible for the significantly higher overgrowth observed on tile bottoms at the offshore site, as an increase in depth can result in less energy from hydrodynamic forcing. Maximum wave orbital velocity ($U_b$) - the force responsible for sediment re-suspension and shear stresses that can dislodge larvae (Reidenbach et al. 2009) - was consistently lower at the offshore site. Depth may also have had an effect on the difference in community composition between sites. At the inshore site, organisms that were less susceptible to the effects of moving sediments (those with vertical growth forms, such as hydroids or those that form hard structures, such as bivalves and polychaetes with calcareous tubes) appeared to be more successful. The lower-energy environment at the offshore site may have been more conducive to the recruitment of organisms with soft tissues and tubes (i.e. encrusting colonial ascidians and amphipods) that might be more susceptible to sediment scour. Furthermore, sediment transport data from the ABS at the inshore site show high concentrations of sediment in the wave boundary layer (the bottom 10-20cm, where tiles 1 and 2 were located) during weather events previously described. Between frequent sediment re-suspension and oscillating wave velocities of 30-45cm/s moving the abrading sediments back and forth, the area close to the seafloor appeared to be an extremely harsh environment for a newly settled larva during these time periods. In order to demonstrate the relationship between recruitment results found during this study and physical stress on the bottom tiles on a stack, the difference in percent surface cover between a tile higher up on a stack (tile 4) and a tile low enough to be susceptible to sediment movement but not burial (tile 2) was examined. The greatest difference in percent cover between these elevations occurred during the deployment period with the highest maximum $U_b$ (Figure 9). Similar comparisons using data from the offshore site did not follow this pattern, supporting that physical stress due to wave and sediment movement was less intense at this site due to an increase in depth. Sediment concentration and transport rates were also low at the top of the tile stacks in relation to the bottom, so factors other than shear stress/sediment scour (i.e. an increase in larval availability close to the sea floor) were most likely responsible for the low percent cover observed on the uppermost tiles.



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Season of deployment also played an important role in determining community composition and amount of cover on settlement tiles. The effects of seasonality on recruitment to hard substrata are well-documented; most epifaunal species have seasonal windows of larval recruitment, with maximum abundances occurring during the late summer and declining to a low in the late winter (Osman 1977). Biological signals, possibly from invertebrate larvae, were detected in the water column (some starting a few cm above sea floor and extending to over a meter) by the ABS at the inshore site during several later deployment periods (moderate amounts in July-Aug and Aug-Oct periods, and a large amount in Oct-Dec period; see Figure 8). These periods correspond with the highest mean percent cover values at the inshore site on both tile surfaces, so one explanation is that large numbers of larvae present during these months (possibly in patterns of diel vertical migration) resulted in higher recruitment rates on the tile stacks. Vertical patterns of recruitment also appeared less pronounced during the last two deployments at both sites (percent cover was consistently high throughout the stacks), suggesting that a seasonal increase in larval supply may override the effects of physical disturbance during these time periods.

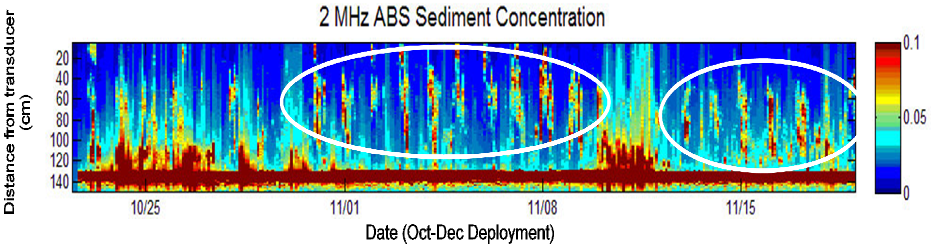

***Figure 9.*** *Biological signals detected by the ABS (2MHz sensitivity) at the inshore site during the Oct-Dec deployment period (strongest signals are indicated by the white circles).*

In summary, a combination of biological and physical factors appeared to play a role in the determining patterns of benthic recruitment on artificial recruitment substrates. Sediment movement may have been detrimental to larvae that settled at close proximity to the sea floor, and this could have implications for the impacts of sediment migration resulting from beach nourishment on natural benthic hard-bottom communities. However, these effects appeared to be more important during seasons when larval availability was a limiting factor to recruitment. More detailed analyses are underway which will statistically compare sediment transport data and percent cover patterns observed on recruitment arrays; this information will be included in a manuscript that is already in progress. Future studies should account for additional biological interactions that were observed in the field but not controlled for in this study (i.e. predation), and include the deployment of a larger number of arrays per sampling site in order to further reduce the extreme within-site variability observed between the stack replicates during several deployment periods.

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## Appendices

***Appendix A**. Summary of benthic epifauna on vertical recruitment arrays. The higher taxa group of each species is indicated next to the species name (A=Amphipod, A.S.=Ascidian (solitary), A.C.=Ascidian (colonial), Br=Bryozoan, Ba=Barnacle, Bi=Bivalve, H=Hydroid, P=Polychaete, O=other taxa).*

| **Species Name** | **group** | **Species Name** | **group** |
|---|---|---|---|
| Actiniaria | O | *Lissoclinum*(?) sp. | A.C. |
| *Aetea* sp. | Br | *Membranipora* sp. | Br |
| amphipod tubes | A | misc tubes | O |
| *Anomia simplex* | Bi | *Obelia* sp. | H |
| Anthoathecatae | H | operculate hydroid | H |
| Arcidae (formerly Barbatia sp.) | Bi | *Ostrea equestris* | Bi |
| *Astrangia* sp. | O | *Parasmittina* sp. | Br |
| *Balanus improvisus* | Ba | *Pennaria disticha* | H |
| *Balanus* sp. | Ba | polychaete tubes | P |
| *Balanus trigonus* | Ba | *Pteria colymbus* | Bi |
| *Balanus venustus* | Ba | sabellarid tubes | P |
| Bivalvia | Bi | Sabellariidae | P |
| *Bougainvillia* sp. | H | sabellid tubes | P |
| *Bowerbankia* sp. | Br | Sabellidae | P |
| *Bugula neritina* | Br | *Schizoporella* sp. | Br |
| *Chelonibia* sp. | Ba | Serpulidae | P |
| *Clytia* sp. | H | serpulid tubes | P |
| colonial ascidian | A.C. | solitary ascidian | A.S. |
| *Corophium* sp. | A | Spionidae | P |
| *Didemnum* sp. | A.C. | *Styela* sp. | A.S. |
| *Ectopleura* sp. | H | terebellid tubes | P |
| Electridae | Br | Terebellidae | P |
| *Ericthonius* sp. | A | *Turritopsis nutricula* | H |
| *Eudendrium* sp. | H | Undet. Hydroid | H |
| *Hydractinia* sp. | H | Undet. Sponge (Demospongiae) | O |