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The Observed Relationship Between Wave Conditions and Beach Response, Ocean Beach, San Francisco, CA

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ABSTRACT

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Understanding how sandy beaches respond to storms is critical for effective sediment management and developing successful erosion mitigation efforts. However, only limited progress has been made in relating observed beach changes to wave conditions, with one of the major limiting factors being the lack of temporally dense beach topography and nearshore wave data in most studies. This study uses temporally dense beach topographic and offshore wave data to directly link beach response and wave forcing with generally good results. Ocean Beach is an open coast high-energy sandy beach located in San Francisco, CA, USA. From April 2004 through the end of 2008, 60 three-dimensional topographic beach surveys were conducted on approximately a monthly basis, with more frequent "short-term" surveys during the winters of 2005-06 and 2006-07. Shoreline position data from the short-term surveys show good correlation with offshore wave height, period, and direction averaged over several days prior to the survey (mean R^2=0.54 for entire beach). There is, however, considerable alongshore variation in model performance, with R^2 values ranging from 0.81 to 0.19 for individual sections of the beach. After wave height, the direction of wave approach was the most important factor in determining the response of the shoreline, followed by wave period. Our results indicate that an empirical predictive model of beach response to wave conditions at Ocean Beach is possible with frequent beach mapping and wave data, and that such a model could be useful to coastal managers.

ADITIONAL INDEX WORDS: *Beaches, Storm Response, Shorelines, Wave Conditions*

INTRODUCTION

Effective coastal sediment management depends on understanding the processes that affect sediment transport at a variety of temporal and spatial scales. Over short timescales (hours to days) storm waves can cause large amounts of sediment movement and thus have the potential to cause significant damage to coastal structures. However, understanding the response of most beaches to storm waves is not a simple task. Capturing shoreline movement with sufficient temporal resolution (e.g. immediately prior to and within hours to days after a storm event) is difficult, and detailed local wave data rarely are available, forcing investigators to rely on parameterizatons of wave climate derived from deep water wave buoy data. While it has been known qualitatively for quite some time that large waves erode beaches, efforts to quantitatively link some measure of wave energy with observed changes in the sub-aerial beach have had a range of success (SONU and VANBEEK, 1971; WRIGHT *et al.*, 1985; FUCELLA and DOLAN, 1996; DAIL *et al.*, 2000; BERNABEU *et al.*, 2003; MILLER and DEAN, 2007; QUARTEL *et al.*, 2008). FUCELLA and DOLAN (1996) showed that for a discrete storm event much of the sub-aerial beach response occurs within the first six hours of a storms onset, and that within the first 12 hours after the storm as much as 50% of the sediment initially lost had been recovered. The rapid changes observed by FUCELLA and DOLAN (1996) highlight that only very high temporal resolution beach

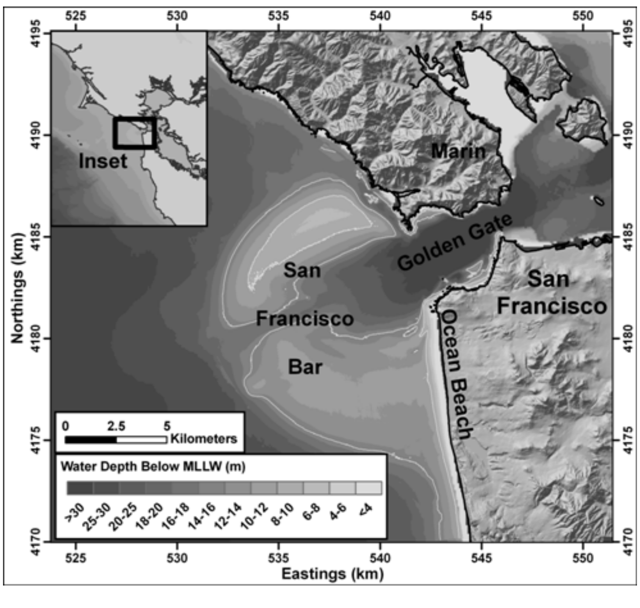

Figure 1. Regional map showing the location of Ocean Beach, the Golden Gate, and the San Francisco Bar. The 10 and 15 m contours are shown in white.

monitoring is capable of capturing the effects of individual storms or extended periods of high waves. Recent advances in video imaging technology and processing (e.g. ARGUS, HOLMAN *et al.*, 1993) have made it possible to define shorelines at very high temporal resolution (up to sub-daily), but the spatial scale of an individual video system is limited and video systems are expensive and can present significant logistical challenges to their installation and operation. Furthermore, in many regions storms rarely occur as distinct events, with most occurring as several sequential events with little to no time in between (e.g. FERREIRA, 2006). Under these conditions effects on the sub-aerial beach can be expected to occur over longer timescales and repeated topographic surveys using standard methods can capture the effects of longer periods of high waves on the beach.

From April 2004 through the end of 2008, 60 monthly or more frequent high-resolution global positioning system (GPS) topographic surveys of the sub-aerial beach at Ocean Beach in San Francisco, CA, USA, have been carried out to capture the response of the beach to various physical forcings over both short (days) and long (years) time scales. The primary focus of this paper is to quantify the short-term response of the beach and link the response of the shoreline from 14 surveys that were collected within 11 days of the previous survey to the wave climate observed between the surveys.

Ocean Beach is a 6.5 km long north-south trending beach located just south of the entrance to San Francisco Bay (Figure 1). The proximity of Ocean Beach to the Golden Gate, the sole entrance to San Francisco Bay, creates both strong (~1 m/s) alongshore tidal currents and variable nearshore bathymetry from a large (154 km^2) ebb tidal delta whose southern lobe attaches to Ocean Beach (Figure 1) (BARNARD *et al.*, 2007). This region of the California coast is exposed to wave energy from both hemispheres of the Pacific Ocean with a majority of year round energy arriving from the west to northwest. Annual mean offshore significant wave height is 2.4 m, but winter offshore significant wave heights frequently reach 4 m and can exceed 9 m (COASTAL DATA INFORMATION PROGRAM [CDIP], 2008). During one five month instrument deployment in winter 2007/08, acoustically measured nearshore (~11 m water depth) maximum wave heights exceeded 10 m (HANSEN AND BARNARD, USGS, unpublished data). Variable nearshore bathymetry creates significant alongshore variations in wave height (up to a factor of 1.5; ESHLEMAN *et al.*, 2007) and complex sediment movement patterns (BARNARD *et al.*, 2007; HANSEN, 2007).

Ocean Beach's urban location has led to considerable coastal development. Chronic erosion of the southern portion of Ocean Beach has claimed portions of two recreational parking lots and currently threatens a major roadway and underground infrastructure associated with a municipal waste water treatment facility. However, while the southern end of the beach has lost sand the northern end has shown significant accretion (BARNARD *et al.*, 2007).

METHODS

Topographic beach surveys were conducted using an All Terrain Vehicle (ATV) equipped with a GPS receiver and antenna operating in either differential (DGPS) or Real Time Kinematic (RTK-GPS) mode. The receiver was programmed to collect position and elevation data once a second (see MORTON *et al.*, 1993 and; DAIL *et al.*, 2000 [appendix] for information on GPS beach surveying). A typical survey contains approximately 15,000 georeferenced elevations which are then gridded to produce a three dimensional surface. Each data point has a conservatively estimated random error of 5 cm in both the horizontal and vertical

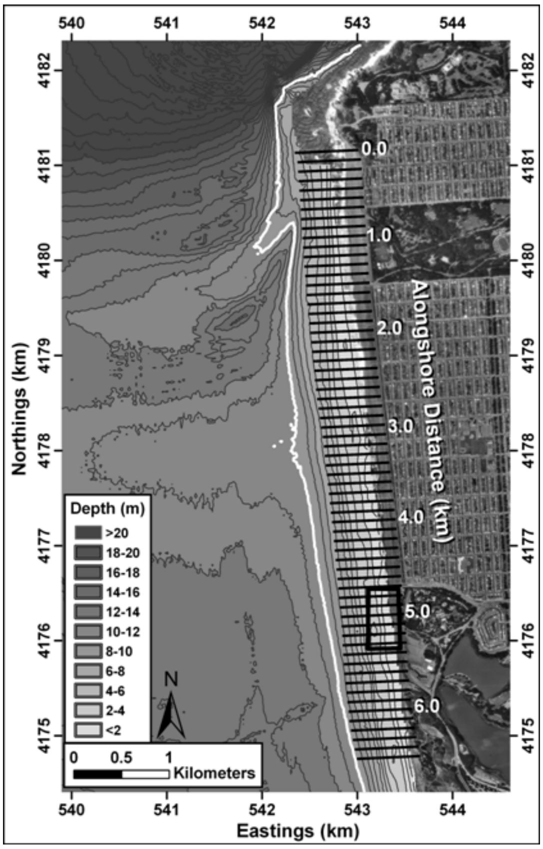

Figure 2. Map of Ocean Beach showing the location of 130 cross-shore profiles where the shoreline position was extracted from each survey (thin black lines, every other shown), alongshore distance scale, area of persistent erosion (black rectangle), and nearshore bathymetry (contour interval 1 m, 10 m contour indicated by white line).

(BARNARD *et al.*, 2007). Due to variations in the aerial extent of each survey, volumetric change was not analyzed; instead analysis was focused on the position of the Mean High Water (MHW) shoreline (1.619 m NAVD88, NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION [NOAA], 2008). A strong correlation between volume change and change in the MHW shoreline has been demonstrated at Ocean Beach (R^2>0.9 for most areas of the beach, HANSEN, 2007) and at other locations (FARRIS and LIST, 2007), indicating that shoreline change is a good proxy for volume change. The MHW contour was extracted from each survey grid and the distance to a fixed shore parallel baseline was calculated at 130, cross-shore transects spaced 50 m in the alongshore using the Digital Shoreline Analysis System (DSAS, THIELER *et al.*, 2005). Movement of the MHW shoreline between each survey was then calculated along each of the 130 transects. To remove local variability in the shoreline the shoreline position was smoothed using a 500 m running mean, thus giving the overall larger scale trend of shoreline movement.

To explore the relationship between wave forcing and beach dynamics, variations in shoreline position were compared to offshore wave data collected at the CDIP Pt. Reyes Buoy, 87 km northwest of Ocean Beach in 550 m of water (CDIP, 2008) and to results from over 4500 SWAN numerical wave model (HOLTHUIJSEN *et al.*, 1993) simulations that calculated wave

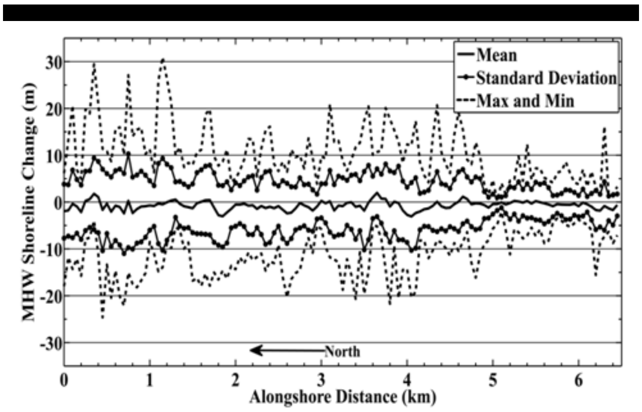

Figure 3. Mean, maximum, minimum, and standard deviation of observed change from all 14 survey sets. Alongshore distance is from north to south in this and all plots.

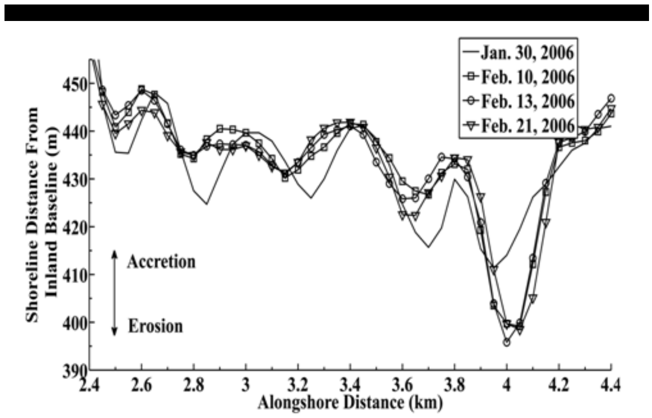

Figure 4. MHW shoreline position relative to a shore parallel inland baseline from four consecutive surveys in the winter of 2005/06. Position is corrected for natural angle of shoreline.

parameters at the 10 m-depth contour offshore of Ocean Beach. For a complete description of how SWAN was used at Ocean Beach readers are referred to ESHLEMAN et al. (2007).

RESULTS

Of the 60 topographic surveys conducted from April 2004 through 2008, 14 were conducted between 2 and 11 days after prior surveys. These "short-term" surveys were conducted primarily during the winters (November-March) of 2005/06 and 2006/07, with two during the summers of 2005 and 2006 (April-October) which were conducted to provide data on the short-term changes of the beach during fair weather conditions (Table 1). MHW shoreline results for all 14 surveys are shown in Figure 3. Mean shoreline change for the entire beach from all 14 survey sets was 0.8 m of erosion, with mean changes at individual profiles ranging from 3.1 m of erosion to 2.0 m of accretion. Changes between individual surveys varied from 30 m of accretion to 25 m of erosion. Daily rates of change varied from as much as 3.9 m/day (accretion) to -6.7 m/day (erosion). If the two summer surveys are removed, as these contribute considerable accretion and are not related to storm events, the mean for each profile is much less uniform and the mean for the entire beach becomes -1.3 m. The observed shoreline change between any two sets of surveys is highly variable – in some cases a several hundred meter stretch of shoreline retreated by as much as 20 m over a three day period as a result of a large berm being removed, while in many instances erosion and accretion were observed at adjacent transects, just 50 m apart. However, if change at individual transects is averaged over several hundred meters in the alongshore the absolute change and the rate of change are greatly decreased, indicating both redistribution of sediment alongshore and alongshore variability in cross-shore sediment transport. For example, shoreline positions from four consecutive surveys in early 2006 suggest that the primary mode of transport over a three week period was alongshore movement of beach cusps with some change in amplitude of these features (Figure 4). During this period offshore wave heights ranged from 1 m to nearly 6.4 m, with offshore peak periods from 8 s to 22 s.

Comparison of the smoothed (using a 500 m running mean) shoreline position data to offshore wave conditions results in relatively good correlations in many locations, although there is significant variation alongshore. Figure 5 shows coefficients of determination (R^2) at each of the profiles for changes in the smoothed shoreline from all 14 survey sets compared to offshore

Table 1: Dates of the 18 "short-term" surveys and mean, standard deviation, maximum, and minimum of observed shoreline change between surveys.

Survey 1	Survey 2	Days Between	Mean Change (m)	Standard Deviation (m)	Max Accretion (m)	Max Erosion (m)
8-Mar-05	11-Mar-05	3	-2.4	4.5	6.9	-20.2
12-Jul-05	22-Jul-05	10	1.0	3.9	16.1	-8.4
22-Dec-05	29-Dec-05	7	-7.3	6.3	1.4	-22.1
24-Jan-06	26-Jan-06	2	-0.9	1.6	2.4	-5.8
26-Jan-06	30-Jan-06	4	0.2	2.8	8.4	-7.8
30-Jan-06	10-Feb-06	11	1.4	5.6	13.6	-20.4
10-Feb-06	13-Feb-06	3	0.8	2.8	11.7	-12.5
13-Feb-06	21-Feb-06	8	0.0	2.5	7.7	-8.3
21-Feb-06	26-Feb-06	5	-0.1	2.4	10.9	-5.6
26-Feb-06	5-Mar-06	7	-2.1	6.0	17.3	-20.5
19-Jun-06	30-Jun-06	11	4.4	10.0	30.9	-24.6
20-Nov-06	24-Nov-06	4	-2.7	3.0	2.6	-16.3
24-Nov-06	5-Dec-06	11	1.1	4.5	15.3	-8.0
5-Dec-06	10-Dec-06	5	-3.8	2.5	0.2	-12.0
	Mean	6.5	-0.8	4.2	10.4	-13.7
	Max	11	4.4	10.0	30.9	-5.6
	Min	2	-7.3	1.6	0.2	-24.6

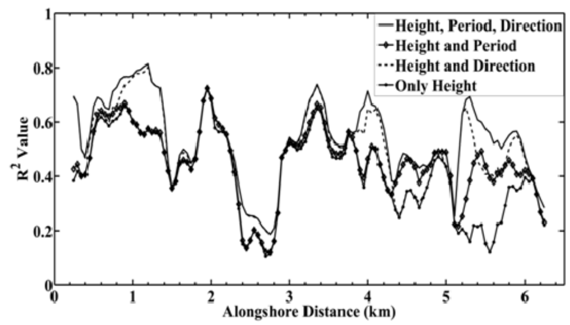

Figure 5. Alongshore R^2 values when the smoothed change in the position of the MHW shoreline is compared to offshore wave conditions.

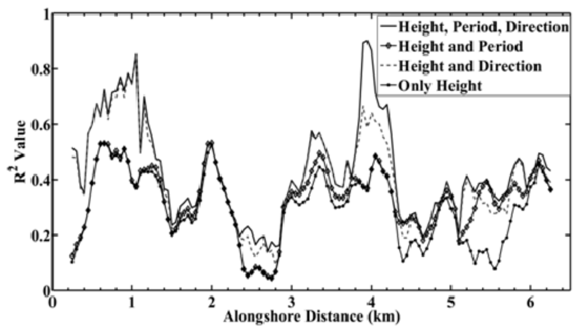

Figure 6. Alongshore R^2 values when the smoothed change in the position of the MHW shoreline is compared to SWAN derived wave conditions at the 10 m depth contour.

conditions averaged over the five days preceding the second survey. Wave parameterization in this analysis included wave period and direction in addition to height as wave period and direction have a considerable effect on refraction across the San Francisco Bar, and thus on the distribution of wave energy along Ocean Beach. The highest coefficients of determination were achieved when offshore wave height, period, and direction were all included, with height and direction or height and period alone being slightly less effective at explaining shoreline change (Figure 5). The degree to which the inclusion of wave period and direction improves the model varies along the beach, but in areas where improvements were noted, wave direction generally was more important than wave period, primarily because wave direction has an important role in regulating wave refraction across the San Francisco Bar. No significant relationship was observed between wave period alone and shoreline change. Inclusion of wave period had relatively little effect on most profiles but improved the model significantly in two regions in the southern portion of the study area, from ~4.4-4.7 and from 5.4-5.8 km alongshore (Figure 5). Model performance varied significantly with the averaging period used for the wave parameters. Averaging over the previous five days produced the highest overall R^2 values (mean for the entire beach 0.54, range 0.19 to 0.81). The peak in R^2 values at five days indicates that this is the typical response time of most areas of the beach, and that shorter term variability in the wave climate may be less important. If different averaging times are used the R^2 values become increasingly worse as a greater averaging interval is used, and become somewhat worse as an incrementally smaller averaging interval is used. Smoothing the shoreline data also improved the model significantly – if the non-smoothed shoreline data is used the range of coefficients of determination increase, with some values being over 0.9, but values are generally lower and the mean for the entire beach decreases to 0.43. The greater range in these results appears to be a direct result of local oscillations in the shoreline like those shown in Figure 4.

Results from the SWAN simulations were used to determine the nearshore significant wave height, period, and direction at the 10 m contour (white line in Figure 2). The wave height and direction at this depth should include the majority of modifications to the offshore height and direction due to refraction, shoaling, and frictional losses. Figure 6 shows the results of the multiple regression analysis using the 10 m contour SWAN wave results in place of the offshore wave data. As with using the offshore data, averaging wave conditions over the previous five days produced the best relationship between wave conditions and shoreline change. While some regions of the beach show higher coefficients of determination (R^2 up to 0.9) than were obtained using offshore wave data, the mean for the entire beach (R^2=0.43 for the height, period, and direction model) actually is less than that obtained using offshore wave conditions. After wave height, wave direction still is the second most important factor even though wave direction at the 10 m contour is much closer to shore-normal than offshore.

DISCUSSION

The change in the MHW shoreline position at Ocean Beach over short periods of time is highly variable, with beach erosion and accretion sometimes occurring on adjacent transects just 50 m apart. Averaging the observed change over 500 m in the alongshore removes the local oscillations in the shoreline, which have a typical wavelength of 200-500 m, and provides a better estimate of the local trend of shoreline change and is thus a more valuable measure for comparison to wave conditions. The relationships developed between the smoothed shoreline change and both the offshore and SWAN wave data provide useful information, for example, the greatest amount of overall shoreline erosion is caused by periods of large waves that have offshore directions less than 300.

However, from a coastal protection perspective understanding the movement of the smoothed shoreline can be of limited value if vulnerable structures are located directly landward of local erosional features. Evidence from the complete set of surveys (monthly and short-term) suggest that shoreline features at Ocean Beach often recur in the same area, and almost always are associated with bathymetric irregularities offshore (HANSEN and BARNARD, In review). For example, major shoreline irregularities frequently occur just north and south of where the south lobe of the San Francisco Bar welds to the coast, and onshore of a flood tidal channel at the northern end of the beach (at alongshore distances 2.5, 4.1, and 0.7-1.1 km respectively in Figure 2). Additionally, the region where the coefficients of determination are the lowest for the short-term surveys (alongshore distances 2.2-3.0 km) is a region of the beach where the annual change in the shoreline position is very well correlated (R^2~0.9) to the intensity of the winter wave climate, implying that this region of the beach responds more to seasonal rather than short-term variations in wave height (HANSEN and BARNARD, In review).

Antecedent beach morphology has been suggested as playing a key role in beach response to storm events (e.g. ORTEGA-SÁNCHEZ *et al.*, 2008; QUARTEL *et al.*, 2008). The shoreline data from the short-term surveys at Ocean Beach shows only limited dependence of shoreline change on antecedent beach morphology. One of the few examples seen was the removal of a large berm at the northern end of the beach that developed in the spring of 2005.

This event caused slightly more erosion than would have otherwise been predicted by the general linear trend seen in the remaining data points in this area of the beach. The limited impact of antecedent morphology that was observed could be due in part to the seasonal dominance of the beach profile shape variations found at a majority of Ocean Beach, and the timing of most of the beach surveys. Most of the surveys were carried out during the winter months when the general shape of the beach had already been changed by the extended periods of high waves that occur during this time of year. Antecedent morphology is likely more important at Ocean Beach during the transitional seasons (autumn and spring) when the beach shape is more prone to enhanced erosion if a storm event occurs.

It was expected that using the SWAN nearshore wave heights would increase the coefficients of determination, primarily because wave parameters at the 10 m contour should provide a better estimate of the energy available to move sediment than wave parameters from a single deep-water location. The most likely reasons for the poorer correlations are related to inherent limitations of the SWAN model and the parameterizations used to force the model. These issues are currently being investigated and it is expected that in the future the nearshore model results will improve on the coefficients of determination found in this study.

CONCLUSIONS

With sufficient temporal resolution of changes in the sub-aerial beach and wave conditions it is possible to directly relate observed changes in the shoreline with observed wave conditions, thus producing a quasi-predictive model that can aid in coastal protection and management. Overall, strong relationships (R^2>0.5) were developed between the position of the shoreline and the offshore wave climate over the previous five days. Smoothing the position of the shoreline using a 500 m running mean and including wave direction and period improved the coefficients of determination in most areas of Ocean Beach. Averaging the wave conditions over the five days prior to the survey produced the best results and indicates that this is the typical response time of the shoreline at Ocean Beach to variable wave conditions. The largest observed changes in the position of the MHW shoreline were most frequently associated with the alongshore movement and enhancement of small to large embayments or the removal of accretionary features such as berms. Continued data collection is expected to further improve the robustness of the relationships described in this study which will further improve the quality of information available to coastal managers.

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