INTEGRATING FIELD RESEARCH, MODELING AND REMOTE SENSING TO QUANTIFY MORPHODYNAMICS IN A HIGH-ENERGY COASTAL SETTING, OCEAN BEACH, SAN FRANCISCO, CALIFORNIA

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Abstract: Wave and coastal circulation modeling are combined with multibeam bathymetry, high-resolution beach surveys, cross-shore Personal Water Craft surveys, digital bed sediment camera surveys, and real-time video monitoring to quantify morphological change and nearshore processes at Ocean Beach, San Francisco. Initial SWAN (Simulating Waves Nearshore) wave modeling results show a focusing of wave energy at the location of an erosion hot spot on the southern end of Ocean Beach during prevailing northwest swell conditions. During El Niño winters, swell out of the west and southwest dominates the region, and although the wave energy is focused further to the north on Ocean Beach, the oblique wave approach sets up a strong northerly littoral drift, thereby starving the southern end of sediment, leaving it increasingly vulnerable to wave attack when the persistent northwest swell returns. An accurate assessment of the interaction between wave and tidal processes is crucial for evaluating coastal management options in an area that includes the annual dredging and disposal of ship channel sediment and an erosion hot spot that is posing a threat to local infrastructure.

INTRODUCTION

The challenges of conducting research in high-energy environments are winnowing as technological advances make it possible to gather data remotely in real time, perform sophisticated numerical modeling, and use specially designed survey vessels for optimal data collection despite the presence of energetic conditions. In the shadow of the large ebb tidal delta at the mouth of San Francisco Bay, CA (Fig. 1), the wave refraction patterns and tidal currents at Ocean Beach are complex and spatially and temporally variable. To quantify the physical processes affecting the mouth of San Francisco Bay and determine the cause of an erosion "hot spot" at Ocean Beach, we have employed a multi-faceted approach that links wave data with numerical modeling, periodic three-dimensional topographic beach surveys, cross shore bathymetric surveys using Personal Watercraft, onshore grain-size analysis using a bed-sediment camera, real-time video monitoring, and a multibeam survey covering the entire mouth of San Francisco Bay. This paper provides a broad overview of the aforementioned suite of techniques in the context of quantifying the morphodynamics in a high energy coastal environment. The integrated use of a broad array of modeling, field techniques, and remote sensing enables a more thorough understanding of coastal dynamics.

We are testing two hypotheses for the cause of the erosion hot spot at the southern end of Ocean Beach:

1) The ebb tidal delta has shrunk in extent due to reduced tidal prism- thereby altering wave refraction/focusing patterns and sediment transport pathways.
2) The system is sediment starved due to extensive damming of rivers that supply sediment to this coastal system coupled with a significant decrease in river discharge.

STUDY AREA

Ocean Beach (37°46'N, 122°31'W) is a 7 km-long north-south trending sandy beach that stretches south from a rocky headland near the entrance to San Francisco Bay (Point Lobos) to the bluffs at Fort Funston (Fig. 1). It is strongly affected by tidal currents from the adjacent Golden Gate inlet, as well as wave refraction along the ebb-tidal delta. Ocean Beach is a high-energy, dissipative system, with classic bar-and-trough morphology interrupted by powerful rip currents. The mean annual offshore wave height is 2.5 m, but during winter storms wave heights commonly exceed 6 m (Fig. 2). The peak annual tide range is 2.5 to 2.8 m, with a mean range of 1.28 m. Tidal currents exceed 2.5 m/s during peak ebb flows in the inlet throat, and over 1 m/s along the northern end of Ocean Beach. Ocean Beach is composed of fine to medium grain sand (0.25 mm to 0.55 mm), but grain sizes as large as 1.6 mm have been measured in the spring. The beach slope decreases from 1:15 in the south to 1:30 in the north. Existing sand dunes range from 12 to 67 m in width along the beach and 7 to 10 m in height above MLLW (Mean Lower Low Water) (Moffatt and Nichol Engineers 1995).

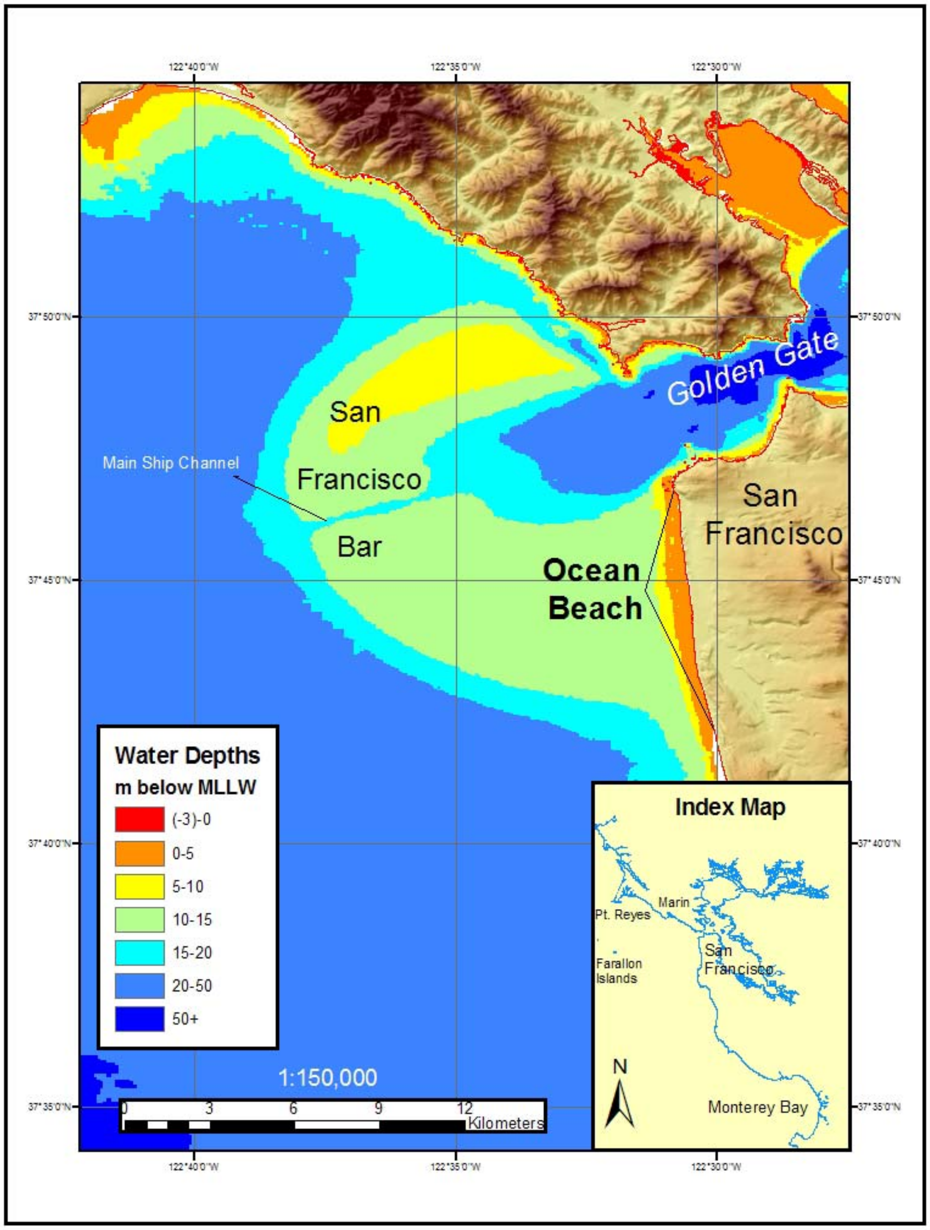

Figure 1. Location of the study area.

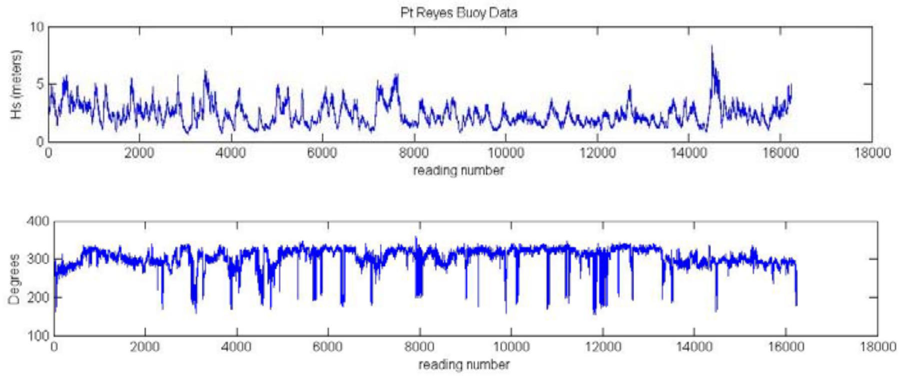

Figure 2. Offshore wave heights and directions throughout a typical year. Data from 2002 Pt. Reyes Directional Buoy (Coastal Data Information Program 2004).

TECHNIQUES AND RESULTS

Beach Surveys

Monthly beach surveys have been conducted using all terrain vehicles (ATVs) with differential GPS. This produces 3D topographic maps with 1-2 cm accuracy of the beach surface. Sets of surveys are then analyzed in a GIS to identify seasonal trends, storm effects, areas of chronic erosion, shoreline position and beach volume changes. Using this technique, we are able to gather over 30,000 survey points in a single 6 hour survey covering the entire 7 km stretch of Ocean Beach. This is far more efficient than traditional base station surveying, where only approximately 1% of the number of survey points could be gathered in the same time. Monthly beach surveys have been conducted since April 2004.

Results from the ATV surveys show typical seasonal patterns of beach erosion during the winter months and accretion during the summer. Superimposed on the seasonal trends, there is a quasi-systematic alongshore alternating erosion/accretion trend at the same wavelengths as the rip spacing at Ocean Beach, ~300-400 m (Fig. 3). In the vicinity of the erosion hot spot at Ocean Beach winter storms cause more dramatic and immediate beach response, with localized monthly shoreline retreat approaching as much 20 m.

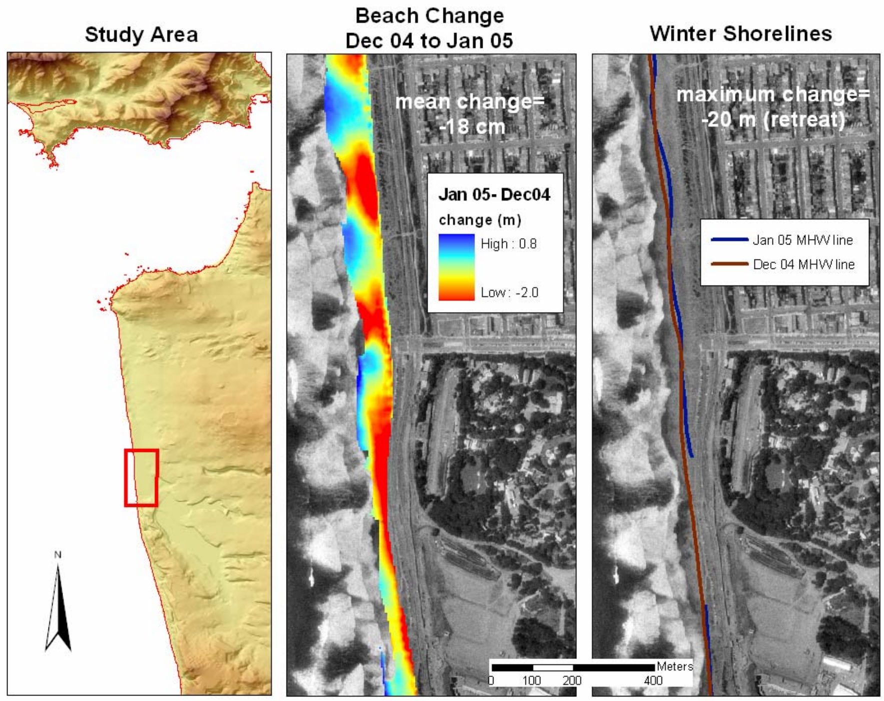

Figure 3. Beach and shoreline change in the vicinity of the erosion hot spot at Ocean Beach during a typical month in winter 2004-05.

Coastal Profiling System

The 3D beach mapping is coupled with cross-shore profiles conducted using Personal Watercraft with kinematic GPS and echo sounder equipment, knows as the Coastal Profiling System (CPS) (Ruggiero et al. 2005). A kinematic GPS base station is set up onshore that allows us to measure depths in real-time with cm accuracy. The survey lines run from 1.8 km offshore through the surf zone to depths approaching MLLW. The survey lines are nested with 250 m spacing where the erosion hot spot persists at the southern end of Ocean Beach (Fig. 4). Quarterly CPS surveys document the changes in beach and nearshore morphology. Four surveys have been completed since May 2004.

The seasonal bar migration signal mirrors the beach response, with as much as 200 m of onshore bar migration between May and November, and nearshore vertical profile accretion as high as 2 m. Initial calculations indicate seasonal cross shore transport rates on the order of 100,000 m^3/ km/yr. The surveys show significant alongshore variation, as illustrated by the three separate profiles in Fig. 4. A well delineated flood channel cuts through Line 3 and the outer surf zone bar is poorly defined due to more complex wave patterns and the strong influence of tidal currents, which exceed 1 m/s during peak ebb and flood flows. Moving to the south, the increasing wave height and influence are represented by more distinct outer surf zone bars and a more pronounced seasonal response of the bar and upper shoreface (e.g. Lines 6 and 14).

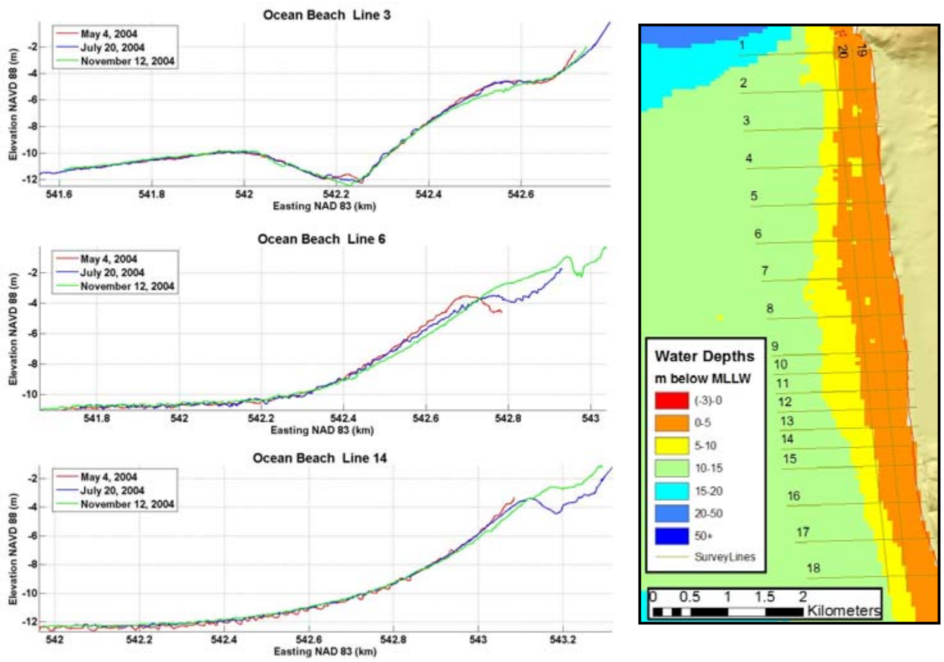

Figure 4. Cross-shore profiles illustrating seasonal bar migration and upper shoreface accretion.

Sediment Analysis
Using a digital bed-sediment camera, grain size surveys are conducted periodically at Ocean Beach as a proxy for tracking variations in the physical energy transporting sediment along the beach. Using MATLAB programs (Rubin 2004), the grain size of the sample in a digital image can be extracted by statistical analysis of the autocorrelation of pixel intensities. The efficiency of this technique allows us to process over 300 images/samples in less than a day, whereas traditional sieving could take several months of work. Four Ocean Beach grain size surveys have been completed since April 2004.

Ocean Beach grain size samples analyzed with both the settling tube and using the digital camera technique are well correlated with r^2 values ~ 0.70 for both median and mean grain size (Barnard et al. 2005, submitted). Median grain size along the beach averages 280 μm, with no significant alongshore variation except for localized coarse lags where median grain size can exceed 1 mm.

Video Monitoring
A web-based camera system was installed at the northern end of Ocean Beach in September 2004, pointing south, to monitor beach and nearshore morphology and processes in real-time. The web-based camera system comprises an analog video

camera and a digital still camera that are housed in a single pan tilt unit linked to a computer and DSL connection. Monitoring Ocean Beach in real-time and archiving all images allows us to track short-term shoreline changes and beach evolution, sand bar migration, rip-channel development and evolution, storm effects and beach evolution (Fig. 5).

Image analysis has been successful in tracking bar and trough migration, validated by the cross-shore CPS surveys. The creation and evolution of rip currents has also been a focus of this study. Bar and trough morphology dominates the quieter summer months (Fig. 5, top) while rip channels become more prevalent during the winter months (Fig. 5, bottom).

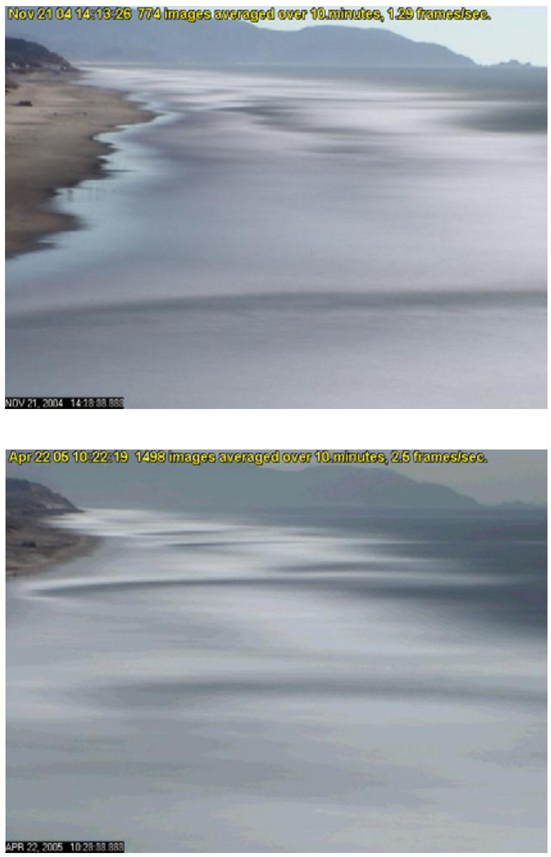

Figure 5. Time-averaged images showing bar and trough morphology and rip-current locations at the northern end of Ocean Beach from November 21, 2004 (top) and April 22, 2005 (bottom).

Multibeam Bathymetry

A multibeam/side scan survey was recently completed at the mouth of San Francisco Bay and including the location immediately offshore of Ocean Beach (Fig. 6). This is the first survey covering this region in almost 50 years.

Analyzing bedform morphology from high-resolution multibeam bathymetry is essential for determining dominant sediment transport pathways and validating hydrodynamic and wave models. The new bathymetry will be a valuable resource as coastal management decisions at Ocean Beach are being made.

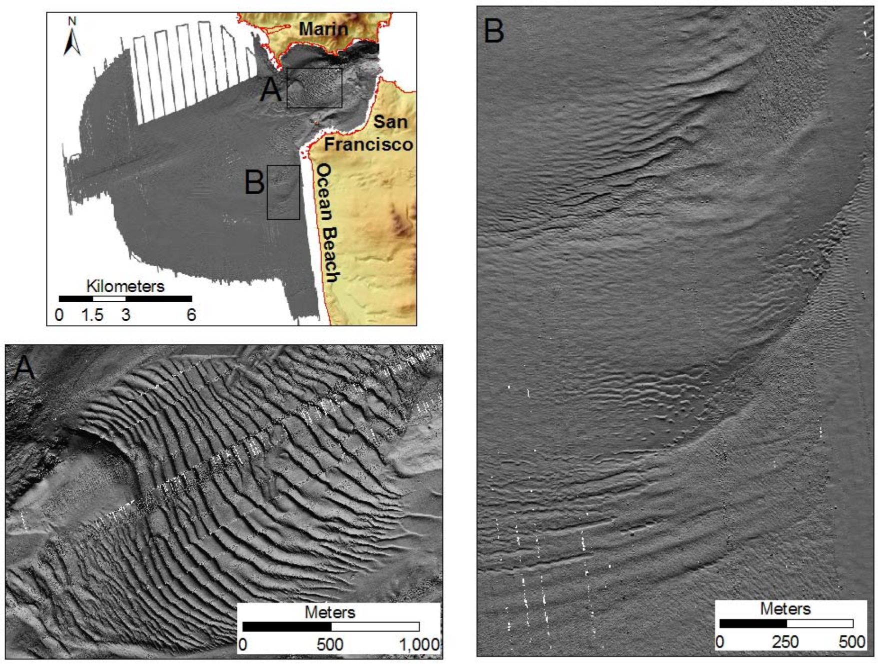

Figure 6. Multibeam map of the study area showing large sand waves at the mouth of San Francisco Bay (inset A) and tide-dominated bedforms moving alongshore at Ocean Beach (inset B).

A comparison of the new bathymetry of this region with the survey conducted in 1956 shows an ebb tidal delta that is generally eroding and shrinking in surface area (Fig. 7). The major erosion pattern along the outer flanks of the ebb tidal delta indicates that waves are becoming increasingly dominant relative to tidal processes. The pattern is consistent with our hypothesis that the tidal prism has been reduced due to bay development over the latter half of the 20th century, thereby reducing the spatial extent of tidal domination. However, the relative abundance of migrating bedforms, particularly the massive sand waves at the mouth of San Francisco Bay (Fig. 6, inset A) and the large bedforms migrating along Ocean Beach (Fig. 6, inset B) reflect an abundance of sediment in the system, indicating that a lack of sediment (hypothesis #2) is not contributing to the erosion hot spot at the southern end of Ocean Beach. The major areas of accretion are along the flood channel adjacent to Ocean Beach and just south of the main shipping channel (labeled SF-8), where the United States Army Corps of Engineers has been disposing of sediment dredged from the main shipping since 1971. Approximately 8 million m^3 of sediment has accreted in this location since the last survey in 1956.

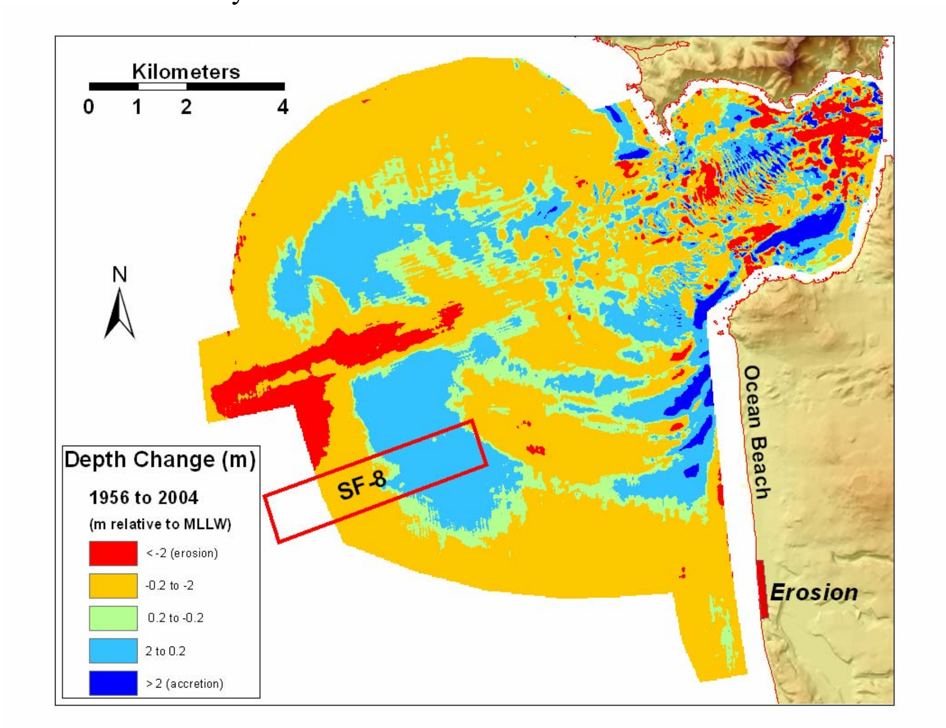

Figure 7. Surface difference map between the 2004 and 1956 surveys.

Modeling

Nearshore processes, including wave refraction, shoaling and breaking, tidal and wind driven circulation, sediment transport, and morphological evolution are presently being modeled for the mouth of San Francisco Bay and Ocean Beach using Delft3D. Delft3D is a model for circulation and morphological evolution consisting of a series of highly integrated modules. The modules utilized for this project include: SWAN/WAV (wave module), SED (sediment transport module), MOR (morphodynamic module), and FLOW (hydrodynamics module) (Delft3D 2004; Lesser et al. 2004). The numerical models we have developed for this region include the finest grid cell spacing placed at the mouth of San Francisco Bay, along the inlet shoreline, and adjacent to Ocean Beach, to obtain high-resolution circulation modeling of the surf zone and immediately offshore.

SWAN predicts the non-steady propagation of short-crested waves, given key boundary conditions that include wind, bottom friction, bathymetry, and water level (Holthuijsen et al. 1993). SWAN is driven using wave data from NOAA Datawell Directional Buoy #29, located 33.6 km west of Pt. Reyes (37^o 56.755' N, 123^o 28.193' W). Simple SWAN runs illustrate the significant variation in wave focusing patterns from two common wave approach angles, owing to the morphology of the ebb tidal delta (Fig. 8). The plots illustrate the importance of shifting wave climate, particularly the southern shift of Pacific storm tracks during an ENSO (El Niño Southern Oscillation) cycle, which results in distinctly different wave focusing and sediment transport patterns at Ocean Beach. The NW swell produces wave focusing adjacent to the erosional hot spot while the focusing pattern shifts to the north during SW swell. However, SW swells refract much less before reaching the southern half of Ocean Beach, breaking at oblique angles, thus setting up strong littoral drift rates and starving the region of sand. The removal of this protective barrier makes the southern part of Ocean Beach susceptible to increased wave attack and erosion during ENSO winters.

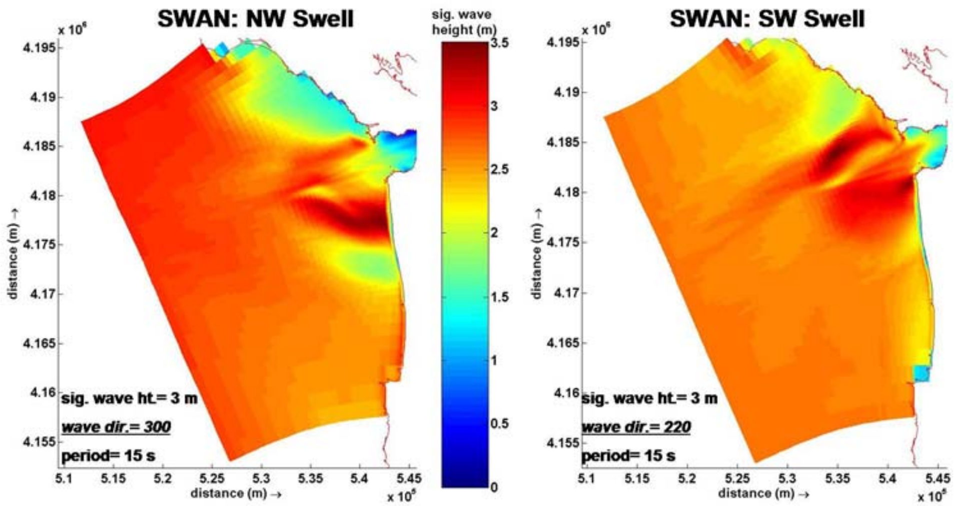

Figure 8. SWAN simulation of a typical NW (A) and SW (B) Pacific storm swell.

The FLOW module has been calibrated using water level measurements from the NOAA tide gauge at Ft. Point and a global tide model, T_tide, to estimate boundary condition tidal constituents for the entire model. At this point, we have been able to model tidal constituents at Ft. Point with > 99% accuracy for the top 8 most influential tidal constituents. A time series of wind and pressure data from the San Francisco Buoy (National Data Buoy Center Station 46026) serve as key atmospheric model boundary input. Our hydrodynamic model also compares favorable with velocity measurements gathered by NOAA during an ADCP deployment from 9/1997 to 5/1998 just inside the Golden Gate Bridge. At present our calibrated model is able to hindcast velocity measurements within 5% at all time steps.

INTEGRATION

Combining a variety of field and modeling techniques has greatly improved our understanding of the coastal dynamics at the mouth of San Francisco Bay and validated our modeling capabilities for this complex region.

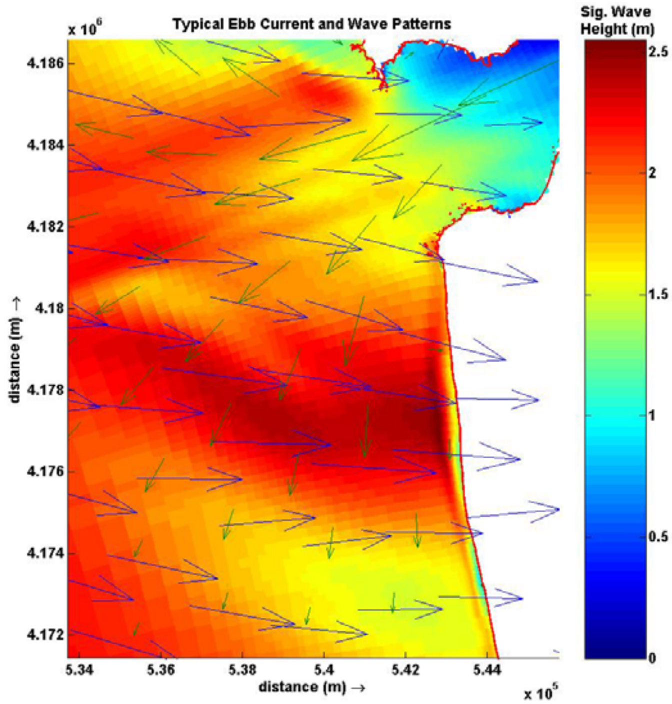

Figure 9. Typical ebb current and wave conditions ($H_{s=}$ 2.5 m, θ_p= 297^o, T_p= 11 s) offshore of Ocean Beach. Blue vectors are wave directions and magnitude and green arrows are tidal current direction and magnitude (range 0-2 m/s).

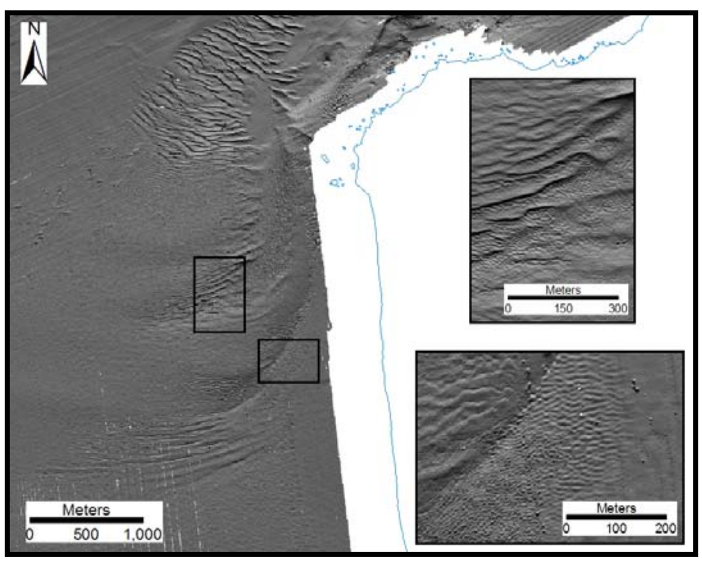

Figure 10. Bathymetry in location of peak wave heights in Fig. 9. Despite large waves, tidal forces dominate while waves only slightly modify bedform

orientation.

The complex wave and tidal current interaction is illustrated in Fig. 9, using outputs from both SWAN and FLOW in Delft3D. The resulting complex bathymetry is reflected in the bedform morphology off Ocean Beach (Fig. 10.) where multibeam data illustrates a flood tidal channel cutting across the nearshore region of Ocean Beach, but also large-scale tide-generated bedforms migrating along Ocean Beach, with orientations that have been slightly modified by the dominant offshore wave direction (297^{o}). The distinct tidal channel was also delineated in the CPS surveys (see Fig. 4, Line 3).

Bedform morphology from the multibeam work has also validated the pronounced and spatially varying current patterns about the region as demonstrated in Figs. 11-12. A strong eddy in the southern half of the inlet throat results in significant return flow during the ebbing tide, and is validated by the large bedform field with distinct flood orientation of the individual bedforms. The powerful ebb jet predicted by Delft3D FLOW in the inlet throat is represented by the huge bedform field immediately west of the Golden Gate entrance. The position of the eddy and its divergence from the ebb jet appear to be very precise, based on the distinct transition from the ebb-dominated tidal jet sand waves to the flood-dominated eddy sand waves (Fig. 12).

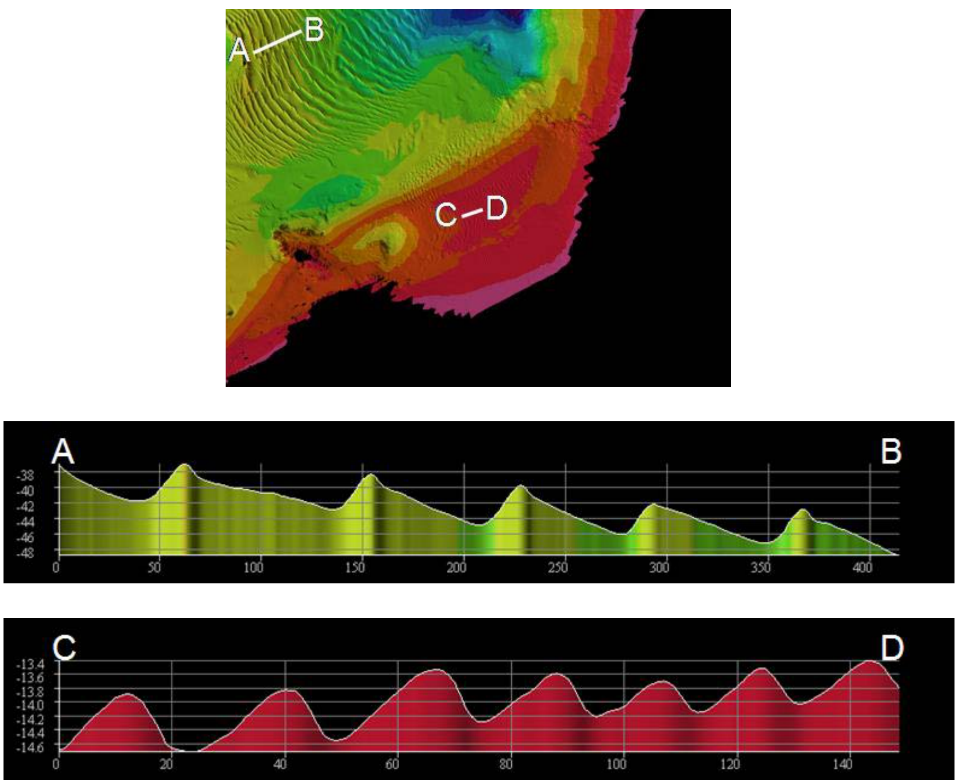

Figure 11. Bathymetry and cross sections across the ebb jet (top, A-B)) and

eddy (bottom(C-D)).

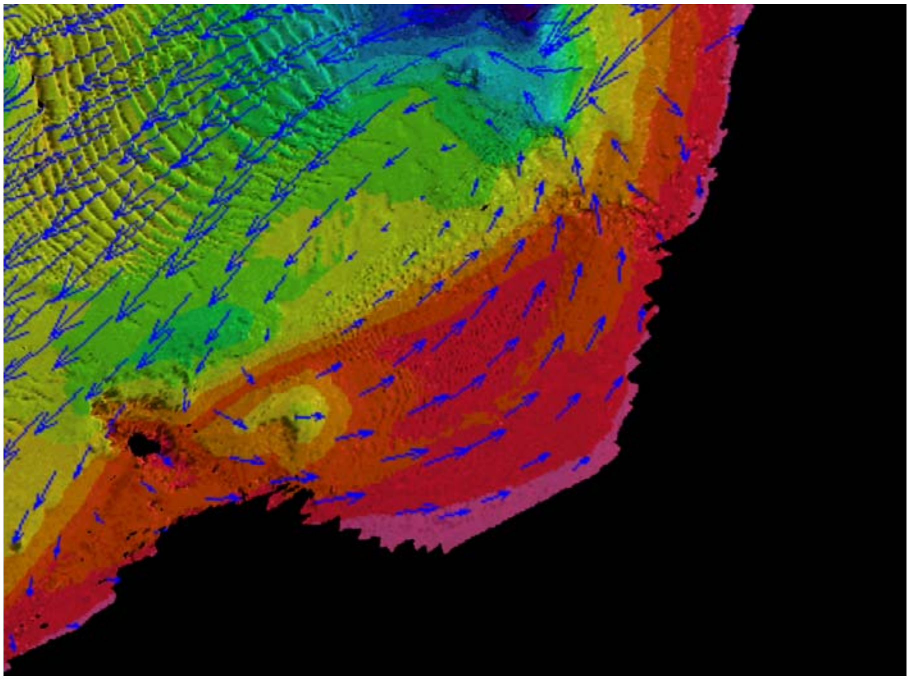

Figure 12. Typical ebb tidal current patterns superimposed on the multibeam bathymetry, illustrating good agreement between predicted tidal currents and resultant bottom morphology.

The short-term morphological response of Ocean Beach is controlled by the nearshore bathymetry and relative tidal influence. The general pattern of erosion offshore of the southern half of Ocean Beach and accretion in the northern half during the last 50 years (Fig. 7) is reflected by the varying response of the upper shoreface and beach surfaces throughout the year, documented by the CPS and ATV surveys (Figs. 3-4). In the southern half of Ocean Beach, where depths have increased and tidal currents have weakened, less wave dissipation by the shrinking ebb tidal delta results in a more dramatic beach response to storm conditions, narrower beach owing to reduced sediment supply to the outer reaches of the ebb tidal delta, and well developed bar morphology. In the northern half of Ocean Beach, the beach has accreted significantly over recent decades, mirroring the offshore signal, and a less distinct bar reflects relative tide domination and increased wave dissipation compared to southern Ocean Beach.

Based on the extensive bedforms that cover much of the region, sediment supply to the system is probably not responsible for erosion at the southern end of Ocean Beach. However, the reduction in relative tidal influence along the outer flanks of the ebb tidal delta has reduced sediment supply to these regions, resulting in delta shrinking. The compression of the ebb tidal delta removed the protective shoals from the southern part of Ocean Beach, and today this region has become an erosion hot spot because it has become exposed to wave attack from most directions and less sediment reaches this portion of the ebb tidal delta.

CONCLUSIONS

Over longer time periods (i.e. decades), tidal processes emerge as the dominant control on coastal evolution in this region, as changes in sediment supply and depositional patterns exert a strong influence on the ebb tidal delta volume and morphology. The ebb tidal delta, in turn, strongly influences wave shielding, refraction, and focusing patterns on adjacent beaches. This is evidenced by the recent multibeam survey that highlights significant morphologic change at the mouth of San Francisco Bay over the last 50 years. Combining a series of observational and modeling techniques has allowed us to determine with confidence the relative contribution of coastal processes influencing the development of the erosion hot spot at Ocean Beach, as well as the dominant sediment transport patterns at the mouth of San Francisco Bay.

ACKNOWLEDGEMENTS

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