Title
Seasonal persistence of a small southern California beach fill

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Overview of Seasonal Sand Level Changes on Southern California Beaches

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1. Abstract

The magnitude of seasonal shoreline fluctuations (the difference between winter and summer subaerial beach width), surveyed repeatedly with airborne LIDAR, varies considerably along 80 km of southern California coastline. The seasonally variable wave field forces seasonal sand level changes, but the alongshore variation of the magnitude of seasonal sand level changes and wave energy are not correlated. For example, along a 20-km reach with little alongshore variation in the wave field, seasonal cross-shore excursions of the shoreline vary by a factor of four. The magnitude of the seasonal beach width changes appears to be influenced by the cross-shore sand grain size difference and may also be affected by alongshore variations in cobbles, exposed bedrock, cliff inputs, and offshore sand supply. A simple equilibrium beach change model, developed using additional in situ surveys at Torrey Pines Beach to tune free parameter values, accurately reproduces the observed seasonal fluctuations in beach width. Ongoing work includes empirically relating the equilibrium model parameters to geologic factors.

2. Introduction

Beach erosion, already threatening much of the U.S. coastline, may increase if sea level rise continues, or if storm frequency or intensity increases. Beach erosion jeopardizes coastal infrastructure and reduces beach tourism. Coastal recreation expenditures in San Diego County beach communities reached $1.7 billion in 1997 (CRA

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1997), but beachgoers indicated they would decrease beach attendance by about 25% if beaches were half as wide or twice as crowded (CDBW and SCC 2002).

The United States Geological Survey (USGS) *National Assessment of Shoreline Change* concluded that 67% of southern California shoreline between Point La Jolla and Dana Point was eroding between 1972 and 1998 (Hapke *et al.* 2006). The design of beach retention and nourishment programs, which are needed to meet recreation demands and protect shoreline and sea cliff property, can be improved by understanding the mechanisms controlling beach change.

Ground-based kinematic Global Positioning System (GPS) surveys (Morton *et al.* 1993) enable sand level change monitoring over several kilometers on individual beaches. Airborne light detecting and ranging (lidar) systems (Brock *et al.* 2002) can sample hundreds of kilometers with high spatial resolution. Repeated lidar surveys are a unique resource for studying large-scale sand level change, but frequent lidar surveys are expensive. In this study, biannual lidar flights were supplemented with monthly or more frequent in situ surveys at selected focus sites to increase temporal resolution.

In southern California, seasonal fluctuations in wave energy cause large seasonal cross-shore fluxes of sediment. Winter storms erode the shoreline, forming an offshore bar, while low energy summer waves cause onshore migration of the bar and shoreline accretion, as observed at Torrey Pines Beach (Shepard 1950; Winant *et al.* 1975; Aubrey 1979). Using lidar and in situ measurements to quantify sand level variability and a regional network of directional wave buoys to monitor wave conditions, the observations show that the magnitude of sand level change varies along the southern California shoreline and that the alongshore variations are not well correlated with alongshore variations in seasonal wave energy.

In other regions of the world, the underlying geology (McNinch 2004), nature and source of beach sand (Jackson *et al.* 2005), and offshore sediment availability (Miselis and McNinch 2006) affect beach morphology. Recent work in southern California (Hogarth *et al.* 2007) explores the offshore geology in depths as shallow as 10 m, but the offshore geology has not yet been related to shoreline beach morphology in southern California. This study shows that the magnitude of seasonal shoreline change in southern California likely depends on swash and surfzone geology, as well as on wave energy.

Many authors have suggested that beaches form stable equilibrium profiles for given wave and sand characteristics (Edelman 1968; Swart 1974; Dean 1977). The equilibrium beach concept is demonstrated with sand level and wave observations at Torrey Pines and incorporated in a simple shoreline change model that assumes cross-shore transport is dominant. Future work aims to relate the values of the free parameters in the shoreline change model to sand characteristics and to include the effect of alongshore sand transport.

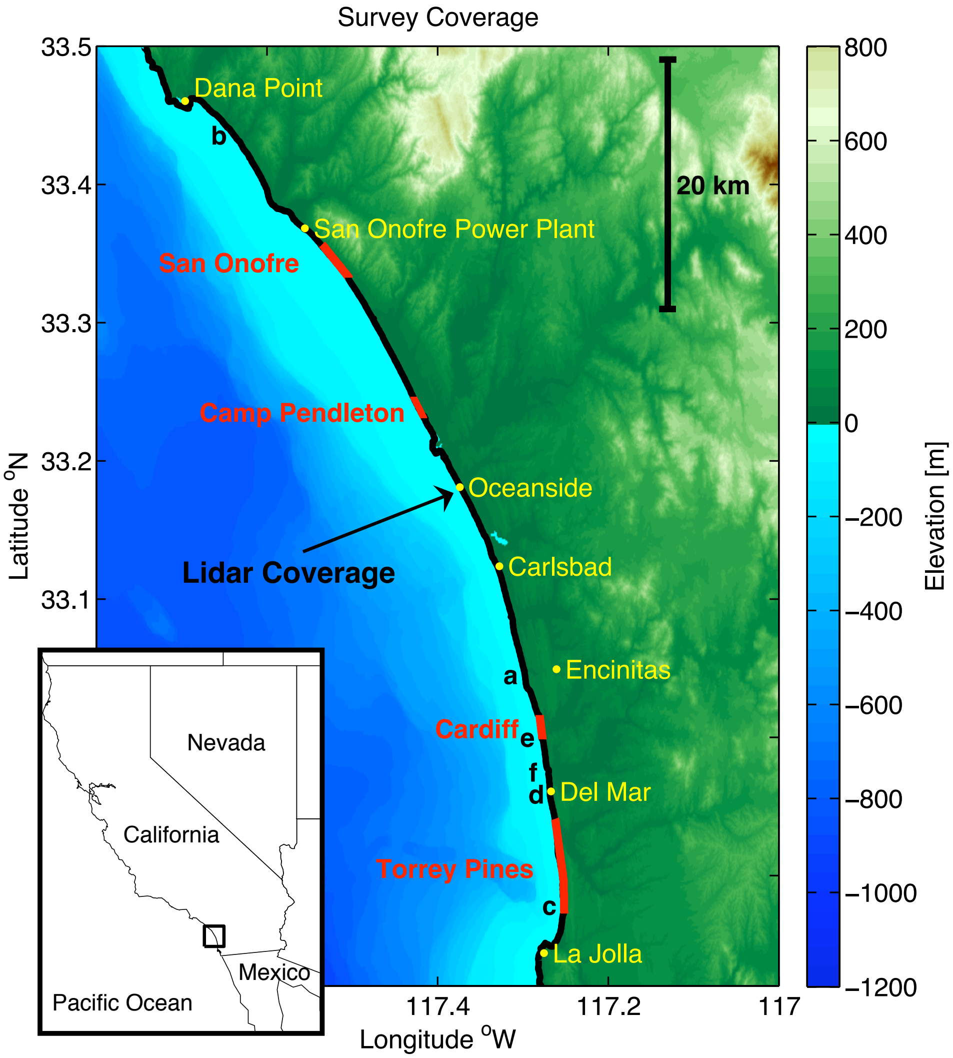

FIG. 1. Lidar (black lines) and in situ (red lines) survey observations are shown along the southern California coastline, with the map location in the inset. The black letters (a-f) locate the images in Figure 5.

3. Sand level measurements

Ten airborne lidar surveys measured sand levels along 80 km of southern California coastline between May 2002 and March 2006 (Figure 1). The processed lidar data includes the subaerial beach, spanning from the backbeach (e.g. cliffs, seawall) to the waterline, where an algorithm using the tide level and wave height removed water data points (Yates *et al.* 2008). In addition to these twice yearly, high spatial resolution surveys, sand levels were measured at four focus sites within this alongshore span (Figure 1, Table 1). Monthly or more frequent in situ surveys spanned from the backbeach to the waterline using a GPS-equipped all-terrain vehicle (ATV).

Three to four times yearly full bathymetry surveys to approximately 10 m depth were obtained using a GPS-equipped ATV, hand-pushed cart, and personal watercraft with sonar. Lidar and in situ surveys both have estimated vertical root-mean-square (RMS) errors of about 15 cm.

4. Sand level changes

Changes in the location of depth contours are dominated by the seasonal cycle. The width of the subaerial beach available for recreation (Figure 2a), characterized by the location of the Mean Sea Level (MSL) contour, narrows (erodes) in winter and widens (accretes) in summer (e.g. dark and light curves, respectively, in Figure 2b), as observed previously at Torrey Pines beach [e.g. Winant *et al.* (1975)]. The magnitude of the seasonal cycle varies significantly over the 80-km surveyed reach. The standard deviation of MSL position or beach width (σ_{MSL}, roughly the RMS seasonal cycle change amplitude, Figure 2c), ranges from about 20 m at Torrey Pines (32.9^{o}N) and Camp Pendleton (33.22^{o}N), to less than 5 m at San Onofre (33.36^{o}N). A typical fall-spring fluctuation, about two times the MSL standard deviation, is often a significant fraction of the total beach width, and in some locations the winter MSL contour nearly reaches the backbeach.

Table 1. Focus site data collection.

Survey site	**Torrey Pines**	**Cardiff**	**Camp Pendleton**	**San Onofre**
Alongshore span (km)	8	2	2.5	4
Survey period	Feb. 2001 - Jul. 2008	May 2007 - Jul. 2008	Dec. 2006 - Jul. 2008	May 2005 - Aug. 2006
Subaerial beach survey frequency	Weekly - monthly	Biweekly - monthly	Monthly	Monthly
Number of exposed beach surveys	90	27	21	13
Full bathymetry survey frequency	Quarterly	Quarterly	Quarterly	Quarterly
Number of full bathymetry surveys	16	7	7	4

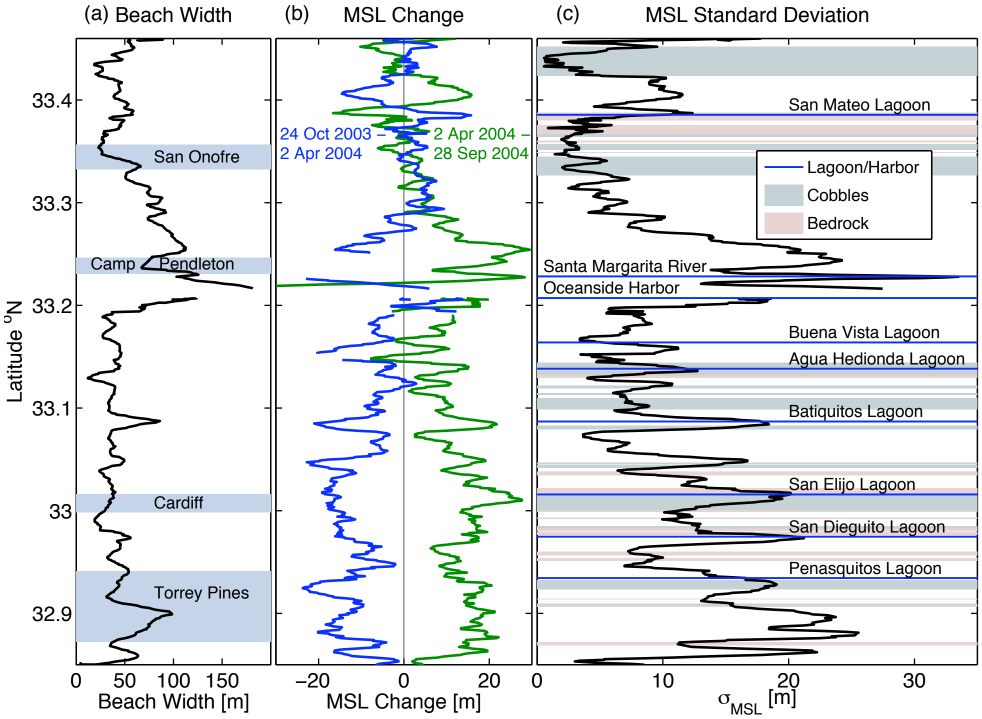

FIG. 2. Lidar-derived beach characteristics versus alongshore location: (a) mean (ten surveys) subaerial beach width, from the backbeach (e.g. dunes, cliffs) to the MSL contour (focus sites are shaded blue), (b) example MSL changes: winter erosion (blue, 24 October 2003 to 2 April 2004) and summer accretion (green, 2 April 2004 to 28 September 2004), and (c) MSL contour location standard deviation σ_{MSL} (seasonal cycle change amplitude). Background shading and horizontal blue lines indicate beach geology (see legend).

To resolve temporally the seasonal cycle observed with biannual lidar surveys, monthly exposed beach surveys and three to four times yearly full bathymetry surveys were acquired for more than one year at selected focus sites (Figure 1, Table 1). Monthly MSL time series, averaged along a 500-m alongshore span (insets, Figure 3), confirm that the biannual lidar observations (Figure 2) are representative of winter and summer beach width extrema. Monthly MSL position moves less than 5 m at San Onofre (inset, Figure 3a) and more than 20 m seasonally at Camp Pendleton and Torrey Pines (inset, Figure 3b,c). The shoreline at San Onofre is stable, not showing a seasonal cycle. Cross-shore profiles, extending from -9 m depth to +3 m elevation (Figure 3), sampled at times of approximate beach width extrema, show that although the beach face at San Onofre is stable, the seasonal cross-shore displacements of contours deeper than about -1 m are as large as 30 m (Figure 3a), comparable to deeper water contours at Camp Pendleton and Torrey Pines (Figure 3b,c). The in situ observations show large seasonal fluctuations of underwater contours at all three focus sites and verify the lidar observations of a stable beach face at San Onofre and large seasonal shoreline changes at Torrey Pines and Camp Pendleton.

5. Wave estimates

Hourly wave spectra are estimated every 100 m alongshore on the 10 m depth contour using a spectral refraction wave model initialized with buoy observations both seaward and shoreward of the Channel Islands (O'Reilly *et al.* 1993; O'Reilly and Guza 1998). The Channel Islands and variable coastline orientation create alongshore variability in seasonal wave fluctuations (Pawka 1983). The average significant wave height is larger in winter (December to April) than in summer (May to November) along the entire coastline, but the seasonal difference decreases from south to

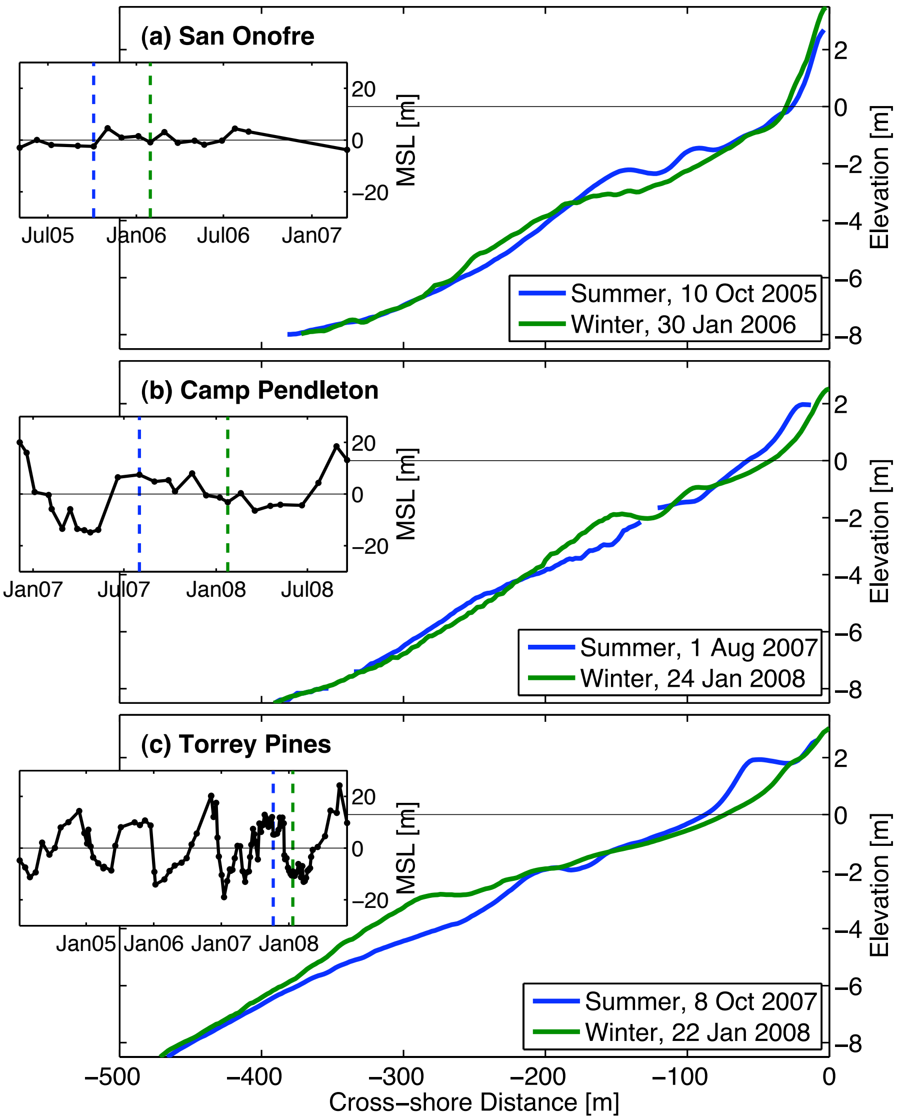

FIG. 3. Summer (blue) and winter (green) cross-shore depth profiles at: (a) San Onofre, (b) Camp Pendleton, and (c) Torrey Pines. Insets show MSL position versus time. Blue and green vertical dashed lines indicate summer and winter profile dates, respectively.

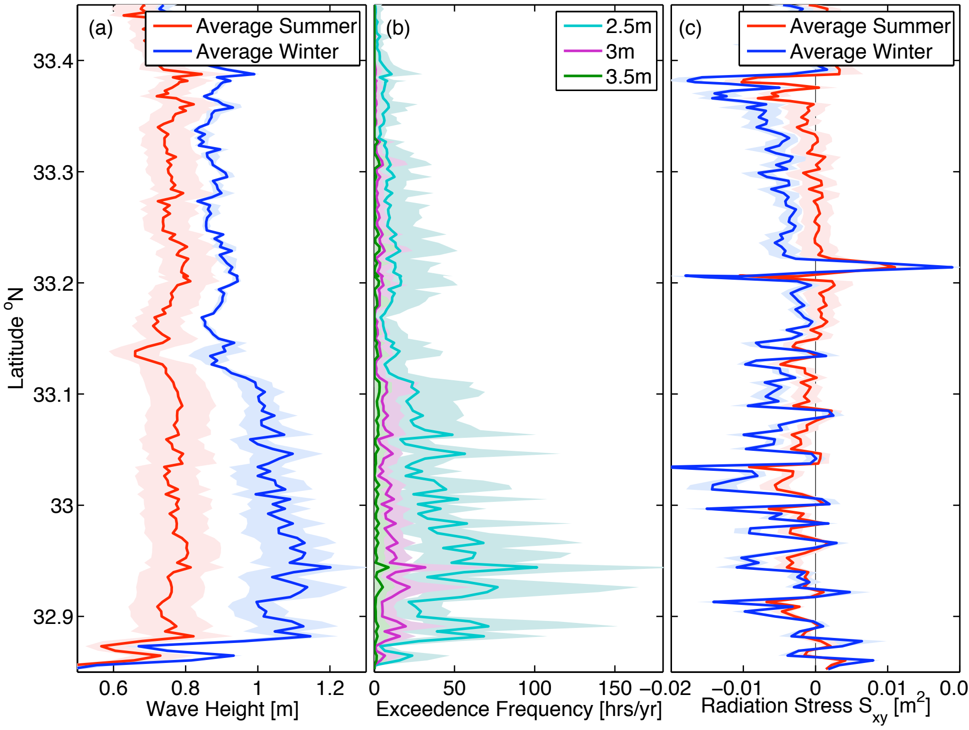

FIG. 4. Seven-year (2001-2007) average wave properties versus alongshore position: (a) average summer (red; May to November) and winter (blue; December to April) wave height, (b) average frequency (number of hours per year) that large (2.5-3.5 m) significant wave heights are exceeded, and (c) average summer (red) and winter (blue) alongshore radiation stress component, S_{xy}. Shading shows the range of mean values in the seven-year record.

north, with a pronounced change around 33.1^{o}N latitude (Figure 4a). Additionally, large wave events are more frequent in the southern region, again with a change around 33.1^{o}N latitude (Figure 4b). The incoming wave direction of storms varies seasonally, with larger winter swell arriving from the northwest Pacific Ocean and generally smaller summer swell arriving from the south Pacific Ocean.

Large seasonal sand level fluctuations occur even on relatively sandy, long, straight beaches and are believed to be caused primarily by seasonal variations in wave height and the associated cross-shore transport (Aubrey *et al.* 1980). However, the magnitude of seasonal beach width changes (σ_{MSL}, Figure 2c) has more alongshore variation than the seasonal standard deviation from the mean wave height (Figure 4a), and these alongshore series are not correlated (R^2 = 0.15). Correlations were also low between the magnitude of seasonal beach width changes (σ_{MSL}, Figure 2c) and the frequency of large significant wave height events (Figure 4b).

Alongshore gradients in the alongshore sediment flux, or the so-called divergence of the drift, can also cause accretion and erosion (Kamphius 1991). The coastline is tilted northwestward (Figure 1), and the radiation stress component S_{xy}, which forces alongshore currents (Longuet-Higgins 1970), is usually directed southward

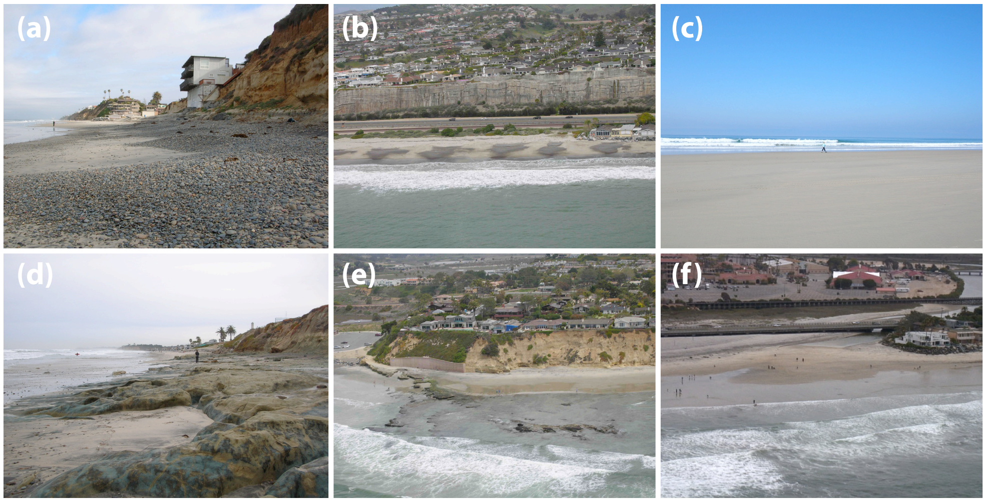

FIG. 5. Visually identified beach features at low tide: (a) thick piles of cobbles overlaying sand, (b) intermittent cobble piles, (c) wide sandy beach, (d) exposed bedrock on the beach face, (e) exposed bedrock in the inner surf zone, and (f) wide lagoon mouth. The image locations are shown in Figure 1.

(Figure 4c). Wave seasonal variability affects the magnitude of the seasonal S_{xy}, but alongshore gradients of S_{xy} are qualitatively similar in summer and winter, and the net alongshore transport does not have significant seasonal variation. Although quantitative analysis is needed, it seems unlikely that alongshore gradients in wave-driven sediment flux cause the observed seasonal alongshore variation in MSL displacement.

6. Beach geology

Visual surveys determined the location of cobbles, exposed bedrock, and lagoons along the 80-km surveyed reach. Some cobbled areas (green shading in Figure 2c) show reduced sand level variability, consistent with suggestions that cobbles armor the shoreline (Carter and Orford 1984; Sherman 1991). However, cobble coverage is both variable and difficult to quantify, ranging from dense cobble layers completely covering the sand (Figure 5a), to small, intermittent piles of cobbles spaced every 50-100 m (Figure 5b), to cobble cusps located only at the backbeach (not shown). While many beaches are sandy (Figure 5c), the depth of the sand layer is often unknown. In some locations, the sand layer has eroded away, exposing bedrock on the beach face (Figure 5d) or in the surf zone (Figure 5e). On beaches with limited sediment availability, bedrock (red shading in Figure 2c) may be exposed in winter when the overlaying sand erodes from the beach face. Additionally, lagoon and river mouths may be a sand source or sink, affecting nearby sediment transport patterns (Figure 5f). MSL contour motions are often large near lagoon mouths (horizontal blue lines in Figure 2c), perhaps owing to changes in lagoon mouth geometry. Non-sandy beach characteristics contribute to alongshore variability in shoreline and depth contour change, but the impact is not yet quantified.

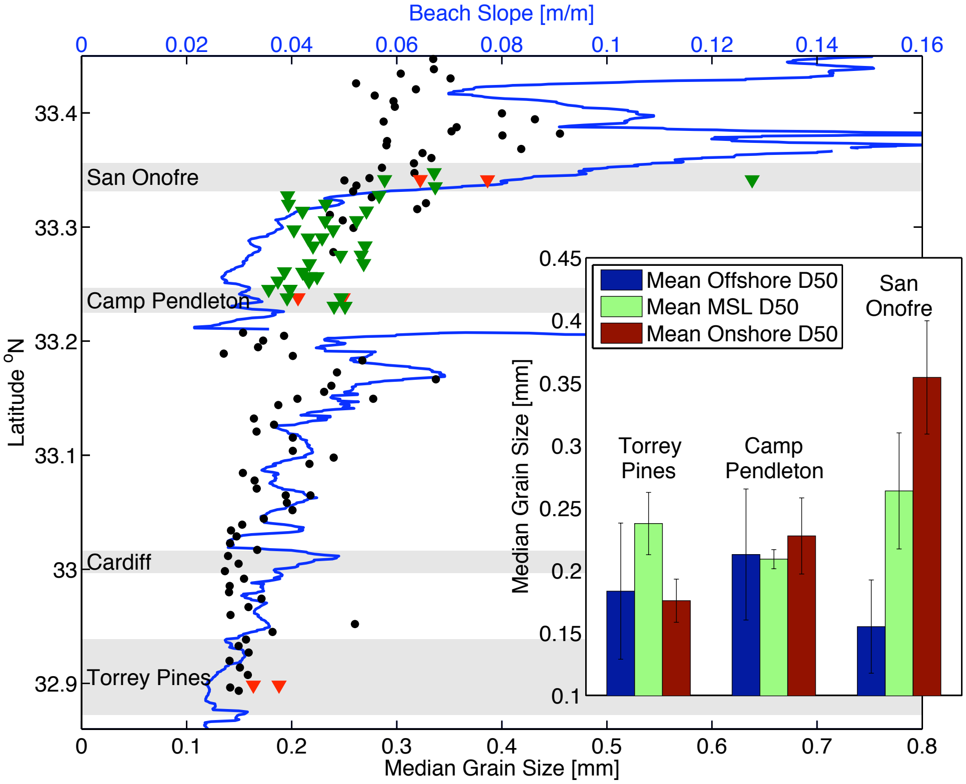

FIG. 6. Median sand grain size [spring 2006, near the high tide waterline (black dots); spring 2007, at +1 m and +2 m elevation (red triangles); and fall 2007, at +1 m and +2m elevation (green triangles)] and beach slope (blue line) versus alongshore location. The inset shows the cross-shore variability of the median grain size (D50) at three survey focus sites.

In addition to visually characterizing beaches, sand grain size was measured approximately every kilometer along the visually located high tide line in spring 2006 (data courtesy of Jen Haas and Neal Driscoll), at three in situ survey sites in spring 2007, and between the Camp Pendleton and San Onofre focus sites in fall 2007 (Figure 6). Wright and Short (1984) characterized beaches as different morphodynamic states using the empirical parameter $\Omega = H_b/w_s T$ (Dean 1973), where H_b is the breaking wave height, T is the wave period, and w_s is the sediment fall velocity, which is grain size dependent. In addition, equilibrium profile response models have included scale parameters, depending on sand grain size (Dean 1977), suggesting that beach responsiveness to waves depends strongly on sand grain size.

The median grain size (D50) on the beach face increases from south to north along the 80-km survey region (Figure 6), with a break in the trend just south of the Camp Pendleton survey site near the Santa Margarita river mouth and the Oceanside harbor and jetty (identified in Figure 2c). Overall, sand grain size decreases with increasing wave height, opposing previous observations suggesting that grain size increases with increasing wave energy (Bascom 1951; Bryant 1982), but consistent with a northern source of large-grained material from the cliffs and littoral transport carrying finer grains southward (Self 1997; Nordstrom 1989). Cliff erosion may provide more than half of the beach sediments in the Oceanside littoral cell (Young and Ashford 2006), and cliff sediment median grain sizes are larger in the northern portion of the study region, between Oceanside and San Onofre, where beach grain sizes are also larger (Haas 2006). Mean beach slope, calculated at MSL +/- 0.5 m also increases from south to north (Figure 6), with a break in the trend at the Oceanside Harbor, following the increase in sand grain size, as shown by Bascom (1951) and others.

In addition to the high tide samples, five sand samples (at approximately -3 m, -1 m, MSL, +1 m, and +2 m elevation) were taken on cross-shore transects at three survey sites and in the region between Camp Pendleton and San Onofre. At San Onofre, grains are coarser on the beach face than in the offshore, whereas the cross-shore sand size variation is weaker at Torrey Pines and Camp Pendleton (inset, Figure 6). A simple measure of the cross-shore grain size difference (α) is:

$$\alpha = \frac{D50_{onshore} - D50_{\mathit{offshore}}}{D50_{onshore} + D50_{\mathit{offshore}}}, \tag{1}$$

where $D50_{onshore}$ is the average of the +1 m and +2 m beach face samples, and $D50_{\mathit{offshore}}$ is the average of the -1 m and -3 m offshore samples (Figure 7b). When α is approximately zero, onshore and offshore grain size are equal. When α is approximately one, sand grains are much coarser onshore than offshore. Between Camp Pendleton and San Onofre, the northward decreasing trend in MSL variability is significantly negatively correlated with α (Figure 7c, R^2= 0.54, significant at 95%), while the seasonal wave height shows little coherent alongshore variation (Figure 7a). We hypothesize that the alongshore variation in beach width change, without corresponding alongshore variation in waves, is related to alongshore variation in α imposed by the sediment source location and characteristics. Alternatively, an unidentified mechanism, such as limited sand supply could also be important. The extent of the offshore sand supply may also limit the volume of sand available to be transported cross-shore to the beach face or between underwater contours. Unfortunately, sand grain size distributions, underlying geology, sand layer depth, cliff contributions, and even inner shelf bathymetry are often unknown over large spatial scales. The limited geological data, and limited understanding of the effect of geologic factors on beach processes, allows only qualitative discussion of the influence of cobbles, exposed bedrock, lagoons, and sand grain size variability.

7. Beach Equilibrium Change Model

Seasonal sand level changes are caused by seasonal variations in waves, and many studies relate wave parameters to beach change [e.g. Miller and Dean (2007)]. Dean (1977) and many others have hypothesized that beaches change toward an equilibrium profile in response to a given wave forcing and that beach change depends on

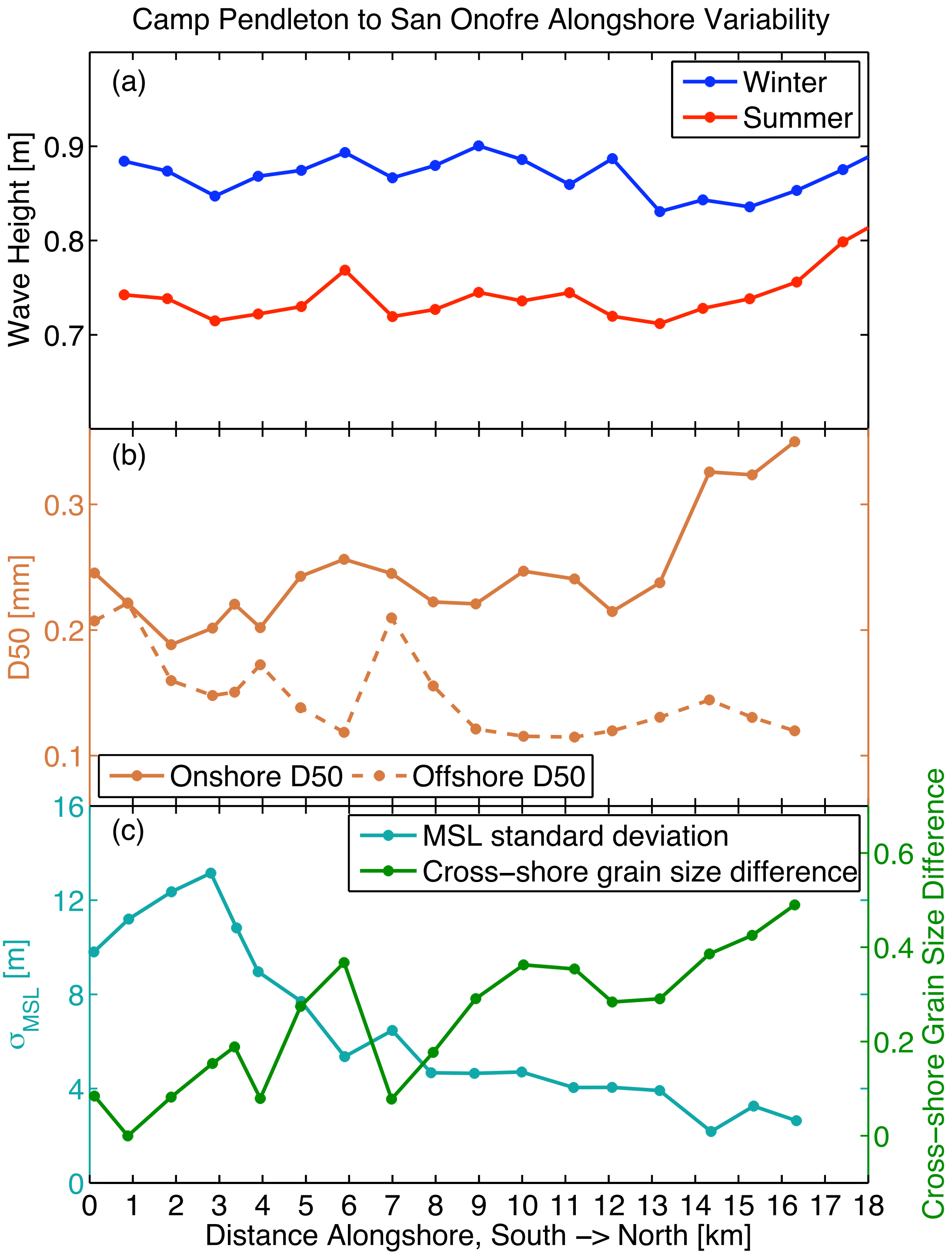

FIG. 7. Alongshore variation between Camp Pendleton (0-2 km) and San Onofre (14-18 km) survey sites: (a) seasonal significant wave height, (b) onshore and offshore median sand grain size (D50), and (c) MSL standard deviation (light blue; σ_{MSL}) and cross-shore grain size difference [green; α, (1)].

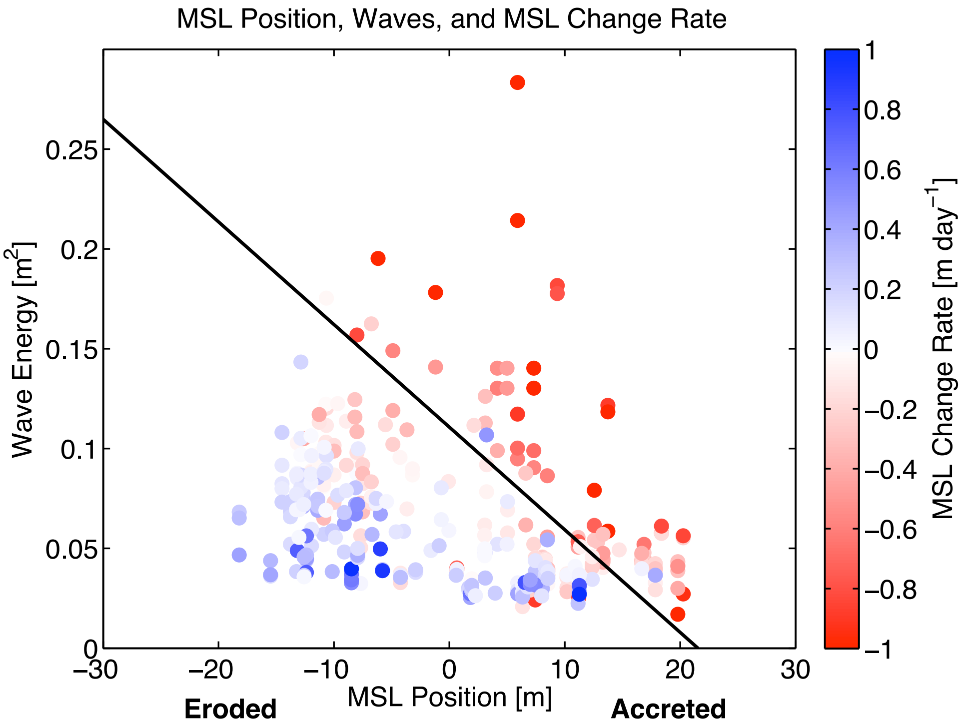

FIG. 8. The observed MSL change rate between two surveys (red is erosion, blue is accretion, and shading shows magnitude) versus initial MSL position and the average wave energy between the two surveys. The solid black line approximates the equilibrium wave condition, which determines the wave energy that causes no further change in MSL position.

both the initial beach state and the wave field. The frequent measurements of sand levels at Torrey Pines are used to demonstrate the power of equilibrium beach change concepts. The model uses three observed quantities: initial beach state (location of the MSL contour, with the time mean removed), beach change (MSL contour movement) between two surveys, and average wave energy (spectral wave energy, units m^2) between two surveys (Figure 8). A line of no change (black line, Figure 8), equivalent to the approximate equilibrium wave condition separating erosional (red) and accretionary events (blue) is determined from the data (by binning the data by MSL state, calculating the zero-crossing from erosion to accretion, and fitting a line through those points). As the beach transitions from an accreted state (positive MSL position; summer) to an eroded state (negative MSL position; winter), the equilibrium wave energy increases: more wave energy is required to erode an already eroded beach. Wright *et al.* (1985) suggested that beach change is proportional to the difference from wave equilibrium (using Deans parameter, Ω, to describe the wave field) times the relative size of the wave event. Following their suggestion but instead using wave energy, the rate of beach width change (dS/dt, where S is MSL position) is:

$$\frac{dS}{dt} = C^{\pm} E^{1/2} \Delta E, \tag{2}$$

where the ΔE is the difference between the wave energy immediately seaward of the surf zone and the equilibrium wave energy [$\Delta E = E - E_{eq}(S)$]. The model has four free parameters: two rate of change coefficients, C^+ and C^- for accretion ($\Delta E < 0$) and erosion ($\Delta E >= 0$), respectively, and two parameters that define the linear equilibrium wave condition as a function of the initial MSL position [$E_{eq}(S) = aS + b$]. The rate of change coefficients [ms^{-1}/m^3] define the magnitude of the MSL change rate for a given difference from wave energy equilibrium times the relative magnitude of the wave event ($E^{1/2}\Delta E$). The observed equilibrium wave energy condition at Torrey Pines was roughly linear (Figure 8), and a more complicated relationship with an exponential approach to equilibrium did not significantly improve model results. The model progresses hourly in time, calculating the difference between the current wave energy E and the equilibrium wave energy $E_{eq}(S)$ for the current beach state at each time step. An optimization technique was used to search the parameter space for the values of the four free parameters minimizing the RMS difference between the observed and modeled MSL position (details in Yates et al., submitted to *J. Geophys. Res.*).

The MSL observations, wave energy time series, and model output at one representative alongshore location at Torrey Pines are shown in Figure 9, where the RMS difference between the model and the observations is 4.0 m (model constants are: C^+ = -1.23, C^- = -0.53 ms^{-1}/ m^3, a = -0.0035 m^2/m, b = 0.12 m^2). The shoreline is eroded particularly rapidly by the first winter storm because the wave energy is significantly higher than the equilibrium wave energy $E_{eq}(S)$ for the wide, accreted summer beach. Recovery rates during low wave energy are slower than typical erosion rates. Wave parameters including H, Ω, Ω^2, wave steepness, and the cross-shore radiation stress (S_{xx}) were used in Eq. 2 instead of E, but model performance did not improve. After the model free parameters have been determined, the model can be used to predict future change given only the wave field (Yates et al. submitted to *J. Geophys. Res.*).

The model framework can be applied at other beaches; however, wave and beach change observations are required to determine the model free parameters. The response coefficients can vary significantly between beaches. For example, at Camp Pendleton, the LIDAR observations and over a year of in situ observations show a seasonal cycle of MSL change with magnitude similar to Torrey Pines, but relatively low wave energy, similar to San Onofre. Different equilibrium conditions and/or rate of change coefficients at these sites may be caused by the different sediment characteristics. The frequency and duration of sand level surveys required to estimate model free parameter values are also being investigated (Yates et al. submitted to *J. Geophys. Res.*).

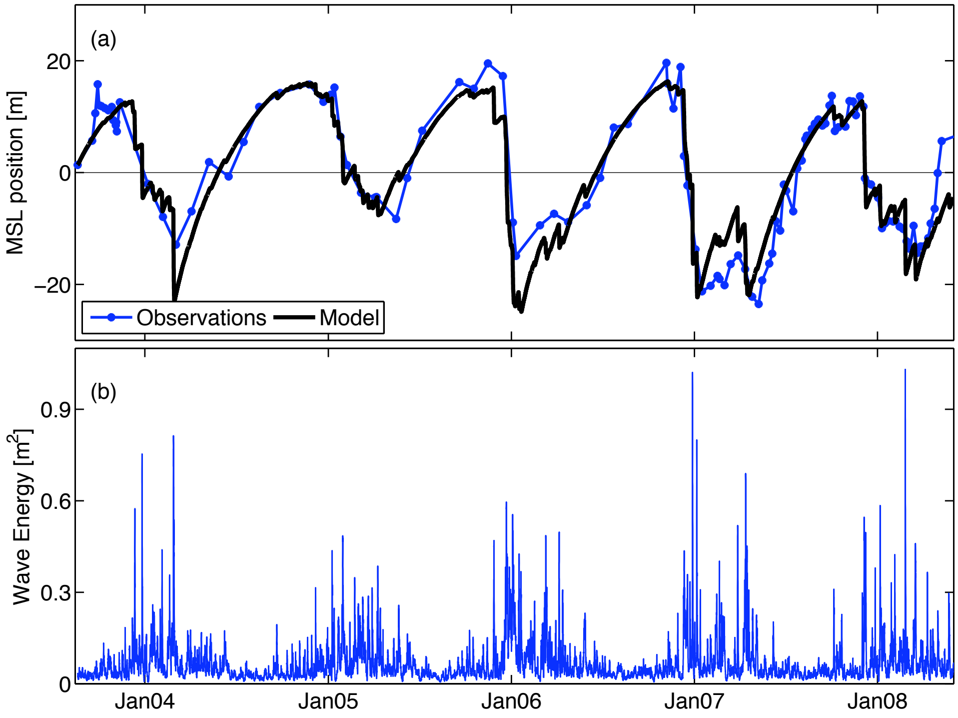

FIG. 9. (a) MSL position (mean removed) versus time: equilibrium model (black) and observations (blue, monthly for 2004-2007, weekly for 2008). RMS difference is 4 m. (b) Wave energy versus time.

8. Summary and future work

The well-known seasonal cycle of sand level changes on southern California beaches (Shepard 1950) shows significant alongshore variability, which is not uniquely controlled by the alongshore variability in waves, suggesting that geological factors influence the seasonal cycle magnitude. Along a 17-km reach with little alongshore variability in waves, the difference between the onshore and offshore sand grain size is negatively correlated with the magnitude of shoreline change. For the same wave energy, shoreline change is less with large cross-shore variations in grain size, with relatively coarse sand at the shoreline. Additionally, exposed cobbles and bedrock, available sand supply, cliff sediment input, and lagoon mouths may have significant, but unquantified effects on seasonal morphological changes.

A simple equilibrium beach change model was developed and calibrated with observations at Torrey Pines and reproduced well the seasonal sand level fluctuations at Torrey Pines. The model can be applied at other locations, using observations of local sand levels and waves to find the model free parameters. Alongshore differences can be explored by comparing the relative magnitudes of the free parameters and their dependence on beach characteristics.

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