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Estimating Changes in Near-Shore Bathymetry with Subaerial Surveys

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ABSTRACT

Surveys of the subaerial beach (e.g., landward of approximately the MSL depth contour) are widely used to evaluate temporal changes in sand levels over large alongshore reaches. Here, seasonal beach face volume changes based on full bathymetry beach profiles (to ~8 m in depth) are compared with estimates based on the subaerial section of the profile. The profiles span 15 years and 75 km of Southern California shoreline, where seasonal vertical fluctuations in near-shore sand levels of a few meters are common. In years with relatively low winter wave energy, most erosion occurs above the MSL contour, and subaerial surveys capture as much as 0.8 of the total (relatively small) seasonal beach face volume change. In response to more energetic winter waves, beach face erosion increases and occurs as deep as 3 m below MSL, and subaerial surveys capture as little as 0.2 of the total beach face volume change. Patchy, erosion-resistant rock and cobble layers contribute to alongshore variation of the subaerial fraction of beach face volume change.

1. Introduction

Beach sand levels, important to coastal management and risk assessment, vary over a wide range of spatial and temporal scales (Nicholls et al. 2007; Long et al. 2011; Yang et al. 2012). Changes in subaerial sand levels over large alongshore spans (many tens of kilometers) are often characterized using airborne lidar observations (Sallenger et al. 2002). Surveys are optimally collected at low tide, maximizing the amount of subaerial beach face measured, and MSL is typically the deepest contour surveyed. Errors in the estimated vertical sand levels, typically about 15 cm root-mean-square, are small compared with the $O(1\,\mathrm{m})$ topographic changes associated with large individual storms (Sallenger et al. 2003). Recently, airborne lidar surveys have been used to compare the impacts of El Niños on U.S. West Coast beaches (Barnard et al. 2011; Revell et al. 2011). Subaerial surveys obtained with ground-based lidar and GPS-equipped vehicles are widely used to characterize near-shore sand volume changes over shorter alongshore spans of a few kilometers, but with increased frequency relative to airborne lidar. Subaerial volumes by definition exclude changes below the waterline (nominally MSL). Farris and List (2007) show that changes in "beach width" (e.g., in the cross-shore location of the MSL depth contour) are well correlated with, and a convenient proxy for, subaerial volume change. However, the relationship between subaerial and subaqueous volume changes is unclear. Here, seasonal volume changes above MSL are compared with estimates using profiles extending to ~8 m in depth.

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2. Observations

a. Study site

The 75-km-long San Diego County, California, study region includes wide (100–200 m) sandy beaches backed by low-lying sandy dunes or lagoon mouths, and narrow beaches backed by sedimentary sea cliffs (Moore et al. 1999; Young et al. 2010) (Fig. 1). Most San Diego beaches are low sloped with a northward trend of increasing beach slope (0.02–0.05) and increasing mean sediment size (0.15–0.29 mm) (Yates et al. 2009b).

b. Bathymetric surveys

Bathymetric surveys at Torrey Pines Beach (biannual: winter and summer, 2004–10) are on approximately 100 m alongshore-spaced shore-normal transects (Fig. 1) extending from the back beach to at least 6 m below MSL (Yates et al. 2009a,b). Subaerial and wading depth surveys were collected at low tide using a GPS-equipped all-terrain vehicle and pushcart. At high tide, subaqueous

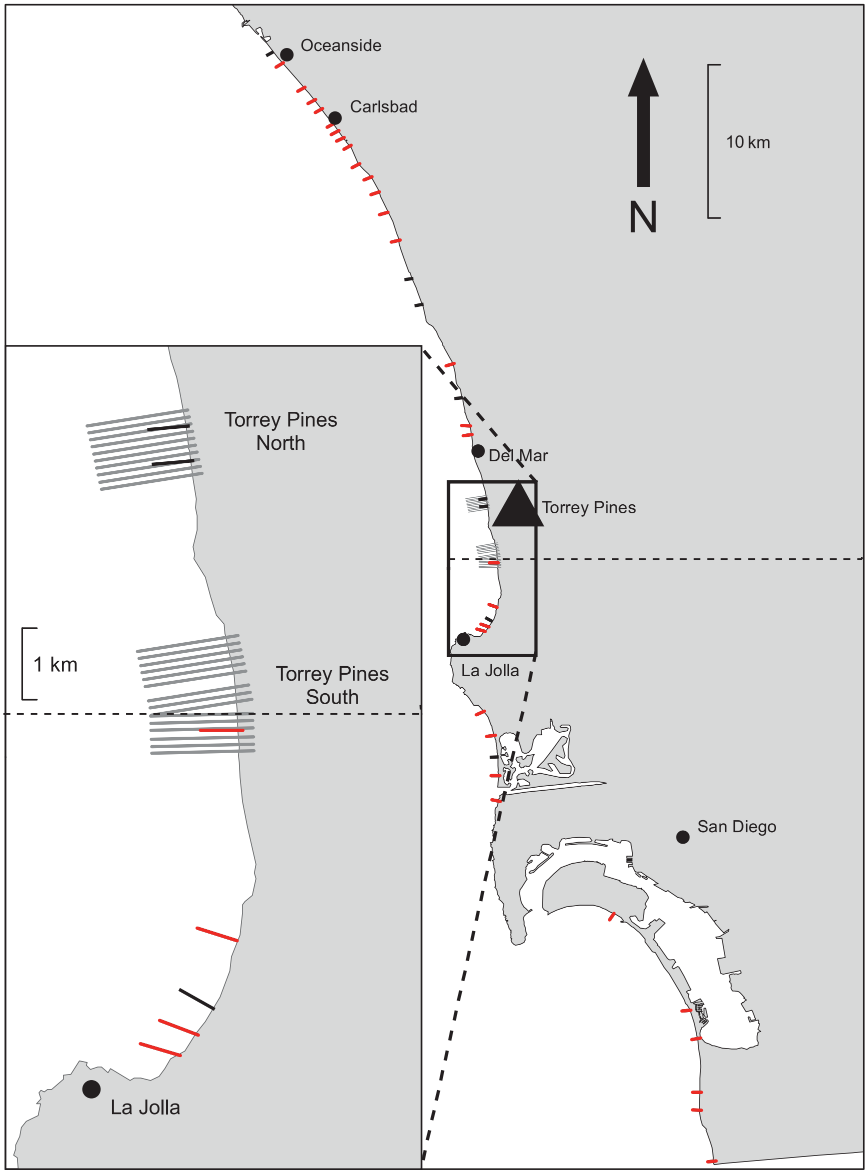

FIG. 1. Map of study region: 38 cross-shore transects (each with at least 20 surveys) span 75 km of San Diego County (red and black markers). Red lines indicate transects with a statistically significant R^2 (see Fig. 6 caption). Torrey Pines focus site (25 transects) is shown in the inset (gray markers). Thin dashed horizontal black line indicates the midpoint separating north and south San Diego County.

sand levels were measured using a GPS-equipped personal watercraft with an acoustic depth sounder (Seymour et al. 2005).

Sand levels throughout San Diego County were surveyed biannually (e.g., fall and spring) for 15 years (1996–2010). These surveys extended to about 8 m in depth with an average alongshore transect spacing of approximately 2 km (see Fig. 1; Coastal Frontiers Corporation 2013). The surveys are broadly representative of accreted summer and eroded winter profiles, and usually do not correspond to the seasonal extrema (see the appendix).

c. *Beach face volume and beach face depth estimation*

Sand level data were gridded every 1 m in the cross-shore, on shore-normal lines, using a 2-m running mean. Transects with cross-shore data gaps greater than 20 m or low overall data coverage ($<30\%$) were discarded.

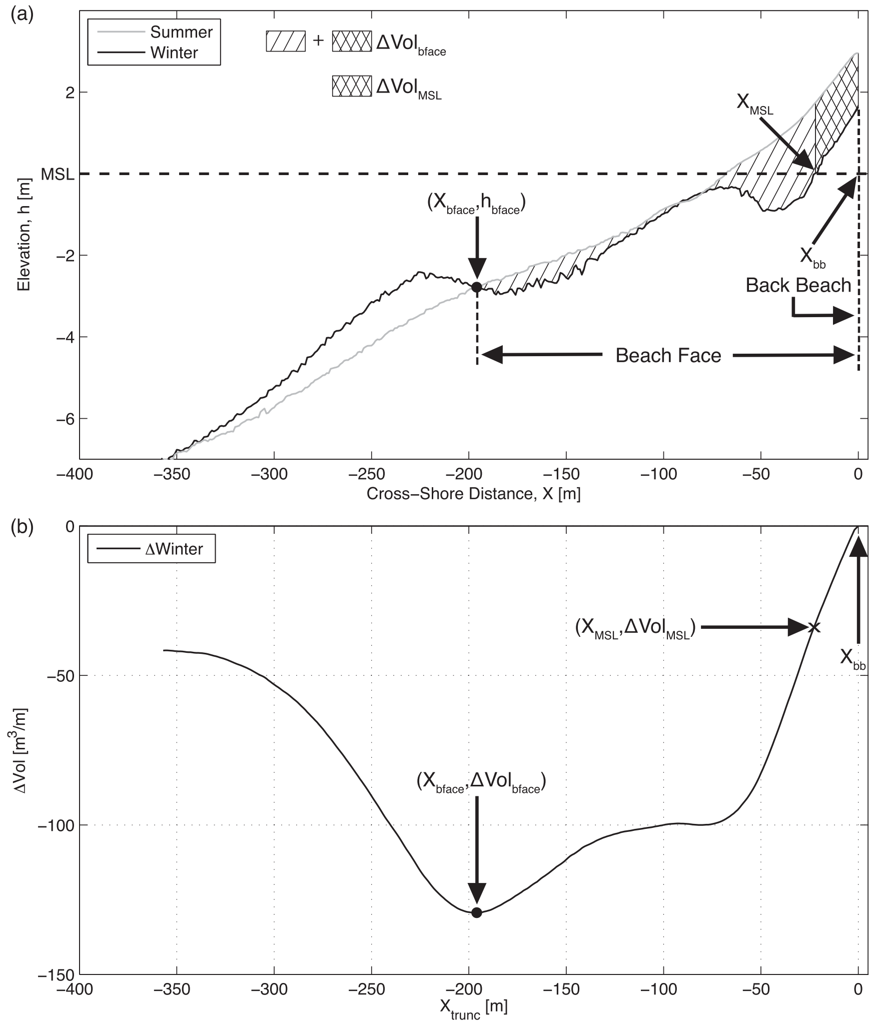

FIG. 2. (a) Depth profiles extend about 350 m from the back beach above MSL to depth $h = -7$ m MSL. Beach face boundary, X_{bface}, at depth h_{bface}, separates depth changes of opposite sign. With the summer profile preceding the winter profile, hatched areas correspond to erosion. Winter sandbar is formed seaward of X_{bface}. (b) ΔVol from (1) is maximum at $X_{\mathrm{trunc}} = X_{\mathrm{bface}}$. Subaerial survey, extending as far seaward as MSL on the eroded profile, captures only ~0.25 of the total beach face erosion (e.g., $\lambda_{\mathrm{MSL}} = 0.25$).

The cross-shore integrated volume change ΔVol between temporally consecutive, gridded cross-shore profiles (Fig. 2a) is

$$\Delta\mathrm{Vol}(X_{\mathrm{trunc}}) = \int_{X_{\mathrm{trunc}}}^{X_{\mathrm{bb}}} [h_{i+1}(x) - h_i(x)]\, dx, \qquad (1)$$

where $h(x)$ is the sand level, subscript i is the temporal survey index, X_{bb} is the fixed location of the back beach, and X_{trunc} is the offshore integration limit. For a subaerial survey $X_{\mathrm{trunc}} = X_{\mathrm{MSL}}$, the location of the MSL depth contour (Fig. 2a). The cross-shore boundary X_{bface} separates regions of erosion from accretion, and is the cross-shore location where (1) has a global extrema (e.g., $X_{\mathrm{trunc}} = X_{\mathrm{bface}}$)(Fig. 2b). The depths at X_{trunc} and X_{bface} are h_{trunc} and h_{bface}, respectively. Each pair of consecutive seasonal profiles yields values of X_{bface} and h_{bface} (Fig. 2a).

The effect of truncating transects on volume change estimates was quantified by varying the seaward limit of volume change between h_{bface} (where all beach face change is captured) and above MSL (Fig. 2b). The fraction of $\Delta\mathrm{Vol}_{\mathrm{bface}}$ captured with a truncated survey is

$$\lambda_{\mathrm{trunc}} = \frac{\Delta\mathrm{Vol}(h_{\mathrm{trunc}})}{\Delta\mathrm{Vol}(h_{\mathrm{bface}})}. \qquad (2)$$

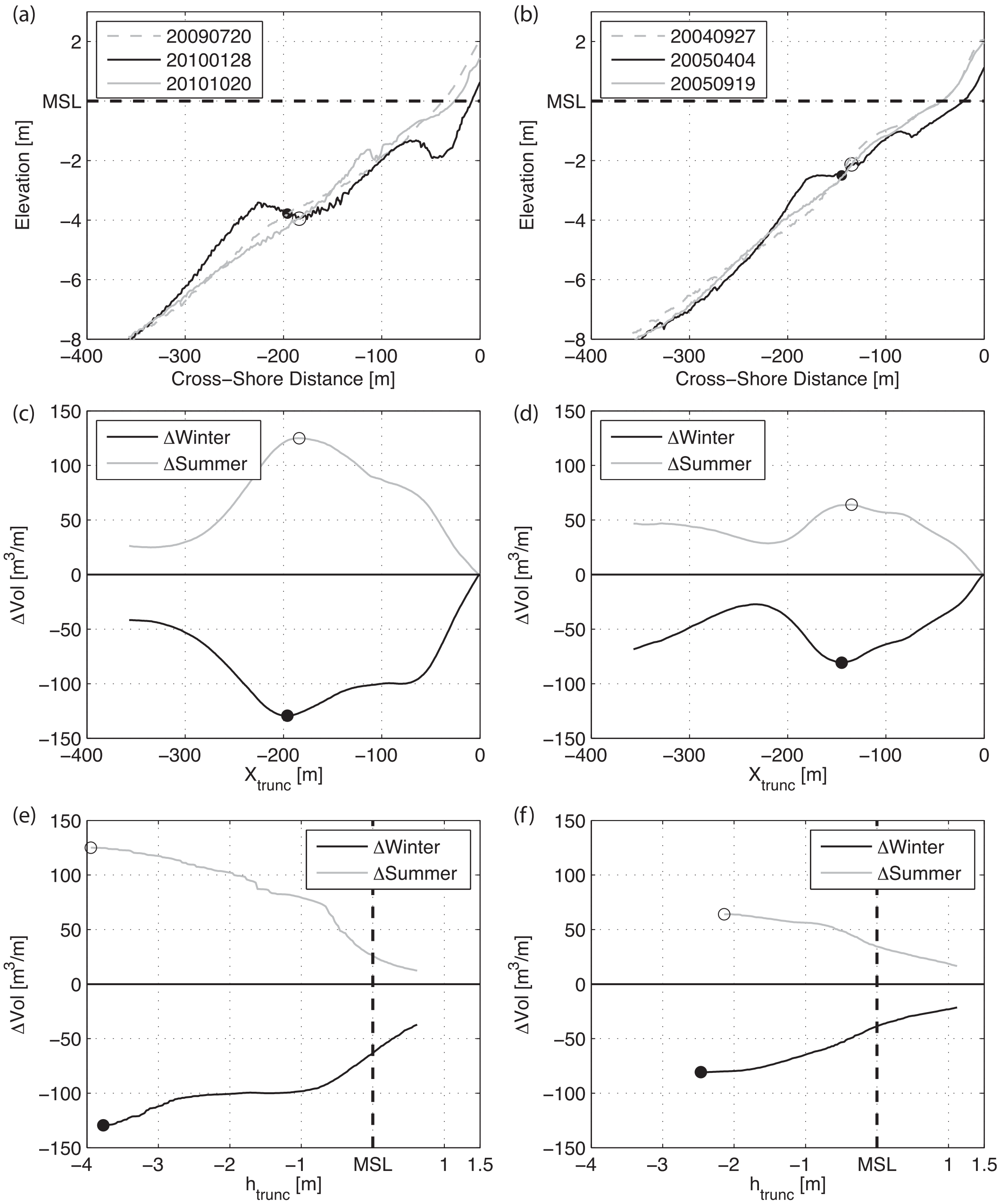

FIG. 3. Seasonal sand level changes on the same transect at Torrey Pines for years with relatively (left) large and (right) small profile changes. (a),(b) Elevation vs cross-shore distance. Black (gray) curves are winter (summer) profiles. (c),(d) ΔVol vs location of cross-shore truncation X_{trunc}. Gray is change from winter to summer (ΔSummer) and black is summer to winter (ΔWinter). Circles in (a)–(d) are the seaward limit of beach face change, X_{bface}. (e),(f) ΔVol vs h_{trunc}, with $h_{\text{trunc}} \geq h_{\text{bface}}$ (circles indicate $h_{\text{trunc}} = h_{\text{bface}}$).

3. Results

A single transect at Torrey Pines (Fig. 3) illustrates a general seasonal beach profile behavior. Large seasonal beach face volume change extends farther offshore, and to deeper depths, than small seasonal changes (Fig. 3; cf. cross-shore locations and depths of circles in the left panels with the right panels). With a small beach face volume change, λ_{MSL} is larger than with a large beach face volume change.

The 10 transects at North Torrey Pines exhibit similar patterns of seasonal change. Seasonal beach face volume changes $\Delta\text{Vol}_{\text{bface}}$, integrated from the back beach to X_{bface} using (1), vary between about 50 and

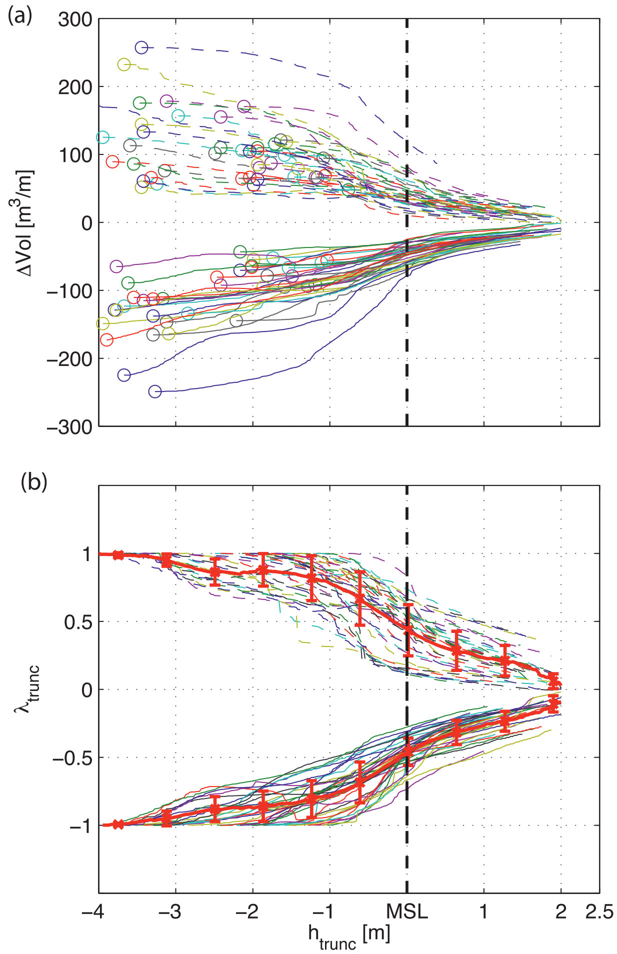

FIG. 4. Seasonal beach volume changes for all 10 North Torrey Pines transects: (a) ΔVol and (b) $\lambda_{\rm trunc}$, both vs $h_{\rm trunc}$, with $h_{\rm trunc} \ge h_{\rm bface}$. In (b) average (red lines) and scatter bars ($\pm$1 std dev) are overlaid. Winter (summer) changes are solid (dashed) curves. Roughly 40% of $\Delta{\rm Vol}_{\rm bface}$ is observed when $h_{\rm trunc}$ = MSL (vertical dashed line). Circles in (a) indicate $h_{\rm trunc} = h_{\rm bface}$.

$250\,{\rm m}^3\,{\rm m}^{-1}$ (Fig. 4a). Beach face change always extended below MSL, and $h_{\rm bface}$ varied between about −0.5 and −4 m (Figs. 4a, 5c,d). Subaerial surveys on average capture 40% of the total volume change (average $\lambda_{\rm MSL} = 0.4$), but the variation of $\lambda_{\rm MSL}$ is large (Fig. 4b). Low $\lambda_{\rm MSL}$ tends to occur with large seasonal volume changes, regardless of season (Fig. 5e). Combined south San Diego transects (locations of significant R^2 in Fig. 6) are similar to North Torrey Pines (cf. left with right panels in Fig. 5; see Table 1). In the few surveys where $\Delta{\rm Vol}_{\rm MSL}$ and $\Delta{\rm Vol}_{\rm bface}$ had opposite sign (Fig. 5b), volume changes were small and the depth profiles crossed several times.

To illustrate general dependences, multiple transects are combined in the regressions of Fig. 5. Analysis of individual transects yields $|\Delta{\rm Vol}_{\rm bface}|$ to $\lambda_{\rm MSL}$ regression slopes usually between −0.002 and $-0.01\,{\rm m\,m}^{-3}$, and slopes for $|\Delta{\rm Vol}_{\rm bface}|$ to $h_{\rm bface}$ between about −0.5 and $-4.2 \times 10^{-2}\,{\rm m}^2\,{\rm m}^{-3}$. A few transects with larger slopes had small volume changes [root-mean-square (RMS) $\Delta{\rm Vol}_{\rm bface} \le 50\,{\rm m}^3\,{\rm m}^{-1}$; Figs. 6a,b, triangles].

4. Discussion and summary

Subaerial surveys, often acquired with topographic lidar (airborne and ground based) or GPS-equipped ground vehicles, are important to beach monitoring. We have compared seasonal volume changes based on the subaerial section of the beach with full depth profiles. The fraction $\lambda_{\rm MSL}$ of total beach face volume change included in a truncated survey from (2) depends on the survey termination depth $h_{\rm trunc}$ and the depth separating profile changes of opposite sign $h_{\rm bface}$ (Fig. 2).

Based on many surveys, winter beach face erosion (and the subsequent summer beach face accretion) extends from the back beach (several meters above MSL) to between about 0.5 and 4 m below MSL (Figs. 5c,d), depending primarily on wave conditions. Wave conditions from any single wave event vary alongshore, owing to sheltering by offshore islands; different sections of shoreline are more or less exposed to ocean swell waves arriving from a particular direction. Typically, relatively energetic winter wave heights are in the 2–5-m range, with periods between 6 and 18 s. In years with energetic waves, the total erosion is relatively large and extends to deeper water. Typical subaerial surveys are limited to MSL and above; $\lambda_{\rm MSL}$ varied between about 0.1 and 0.9 (Figs. 5e,f; Table 1).

At some alongshore locations, erosion-resistant rock, cobble layers, and limited sediment supply can be seasonally important, restricting upper-beach-face erosion. Erosion above MSL reaches a geologically determined limit with moderately erosive waves. Further erosion, in severe conditions, occurs in the region below MSL, which is not sampled by subaerial surveys. Such geological features may contribute to the substantial alongshore variation of $\lambda_{\rm MSL}$ statistics (Fig. 6).

It does not appear possible to reliably estimate full beach face volume changes from subaerial volume changes at alongshore locations lacking nearby historical full bathymetry transects. Naturally, subaerial surveys of beaches with wave climates, tides, and geological settings different from southern California could behave much differently. The conclusion here is cautionary. The relationship between volume changes from subaerial and full profiles is variable and poorly understood.

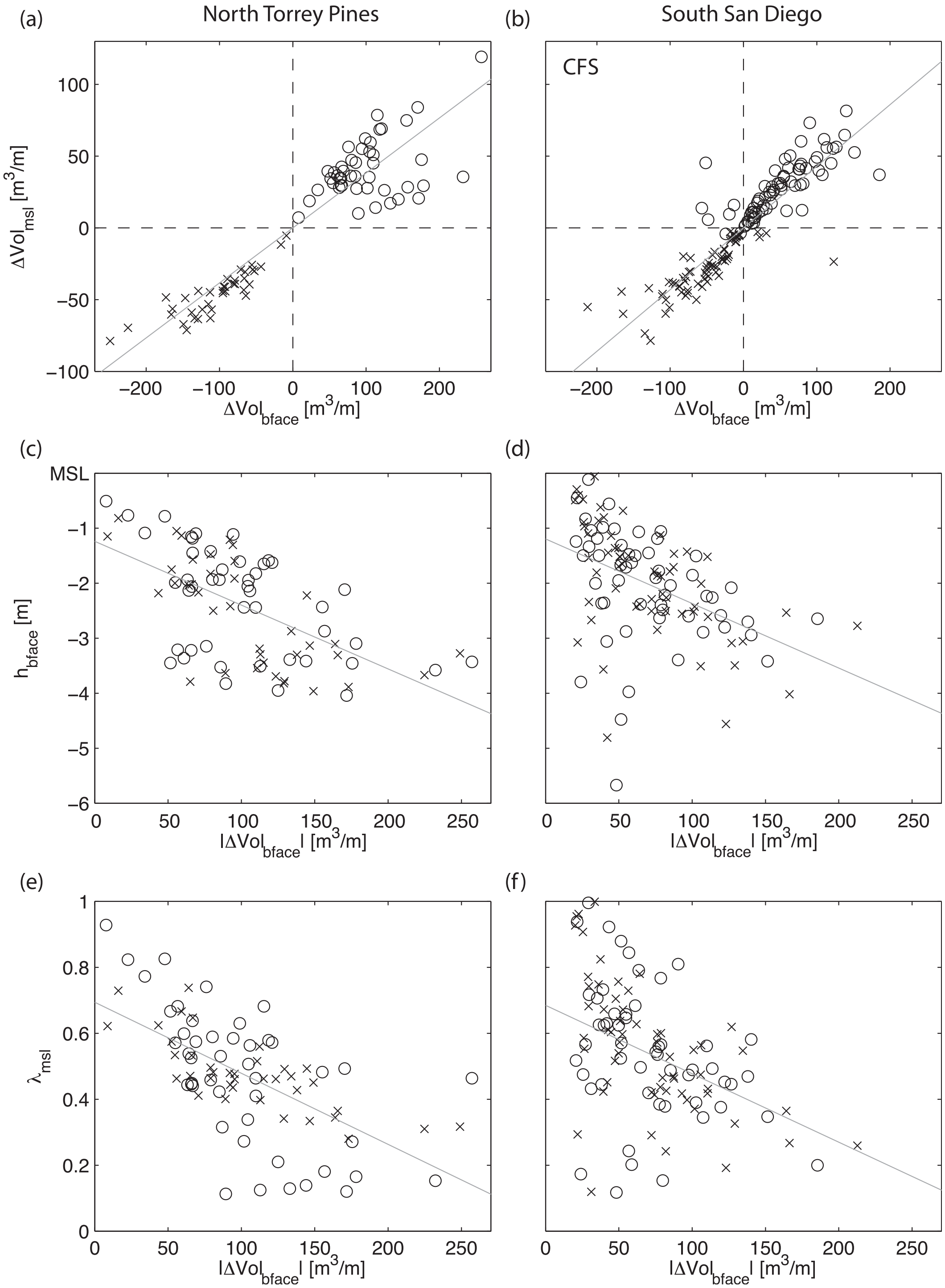

FIG. 5. (left) North Torrey Pines and (right) south San Diego bulk (e.g., many transects) regressions for (a),(b) ΔVol_{MSL} vs ΔVol_{bface}, and (c),(d) h_{bface} and (e),(f) λ_{MSL} vs $|\Delta Vol_{bface}|$. See Table 1 for regression statistics. Summer (circles) and winter (crosses) changes indicated. The six transects included in the bulk South San Diego regressions have significant R^2 when regressed individually for h_{bface} and λ_{MSL}, both vs $|\Delta Vol_{bface}|$ (see Fig. 6).

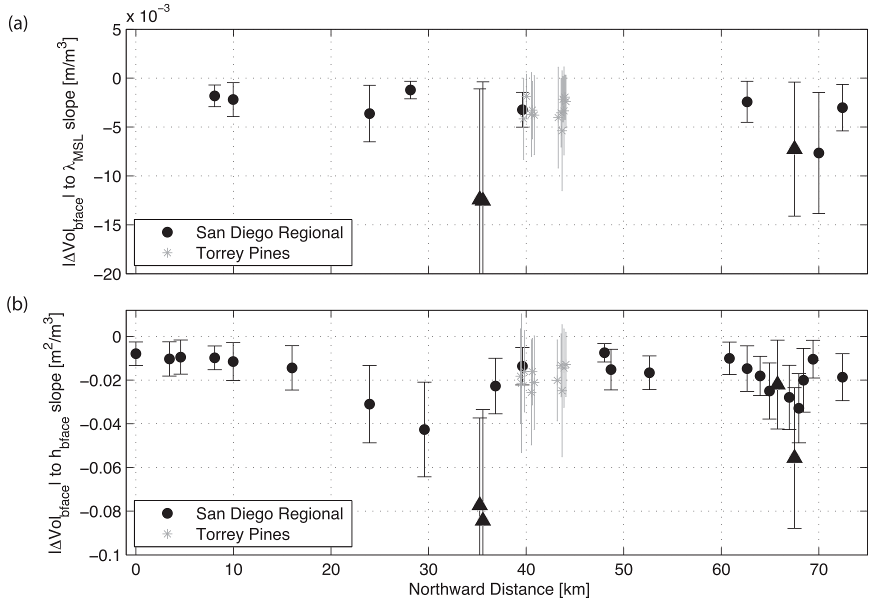

FIG. 6. Regression slopes with 95% confidence intervals for individual transects (a) λ_{MSL} vs $|\Delta Vol_{bface}|$ and (b) h_{bface} vs $|\Delta Vol_{bface}|$, both vs northward distance from southernmost transect. Regression slopes shown are transects with a significant R^2 (Fig. 1, red markers). Transects with relatively small RMS ΔVol_{bface} ($\leq 50\,m^3\,m^{-1}$) are indicated with triangles. Gray color indicates Torrey Pines. Combined northern Torrey Pines and combined southern San Diego bulk regressions are shown in Fig. 5.

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APPENDIX

Biannual Survey Timing

Monthly or more frequent subaerial surveys at Torrey Pines put the biannual San Diego County profiles analyzed in temporal context. The cross-shore location of the MSL contour (a proxy for subaerial volume change; Farris and List 2007) usually does not vary substantially over a few weeks, with the exception of the first winter storm (Fig. A1). Thus, the present volume change results are generally insensitive to shifts of a few weeks in the survey timing. Figure A1 also shows that the depth profiles analyzed, spaced roughly six months apart (fall and spring), do not necessarily correspond to seasonal extremes in beach width. For example, the surveys of May 2007 (eroded winter), October 2007 (accreted summer), and May 2008 (eroded winter) underestimate seasonal change. In those years the winter beach had already recovered by May, and the summer beach had eroded by October. In other years, the surveys are closer to seasonal extrema. Our analysis examines the effect of profile truncation on volume changes, irrespective of the underlying cross-shore and alongshore processes, or the precise timing of the profiles.

TABLE 1. Torrey Pines and San Diego bulk regression slope statistics with 95% confidence limits and R^2, and h_{bface} bulk average and standard deviation; $R^2 > 0.12$ is significant at the 95% level. Corresponding regression plots for southern Torrey Pines and northern San Diego are shown in Fig. 5.

	ΔVol_{bface} to $\Delta Vol_{MSL}(R^2)$	$|\Delta Vol_{bface}|$ to $h_{bface}(R^2)$ ($10^{-2}\,m^2\,m^{-3}$)	$|\Delta Vol_{bface}|$ to $\lambda_{MSL}(R^2)$ ($10^{-3}\,m\,m^{-3}$)	$\langle h_{bface}\rangle(\sigma)$(m)
South Torrey Pines	0.58 ± 0.10 (0.93)	−1.2 ± 0.4 (0.20)	−2.9 ± 1.2 (0.17)	−2.3 (1.1)
North Torrey Pines	0.38 ± 0.09 (0.87)	−1.2 ± 0.4 (0.36)	−2.2 ± 0.7 (0.41)	−2.4 (1.0)
South San Diego	0.43 ± 0.08 (0.81)	−1.2 ± 0.5 (0.20)	−2.1 ± 1.4 (0.17)	−2.0 (1.0)
North San Diego	0.21 ± 0.06 (0.62)	−1.2 ± 0.7 (0.19)	−2.3 ± 3.3 (0.07)	−2.5 (0.8)

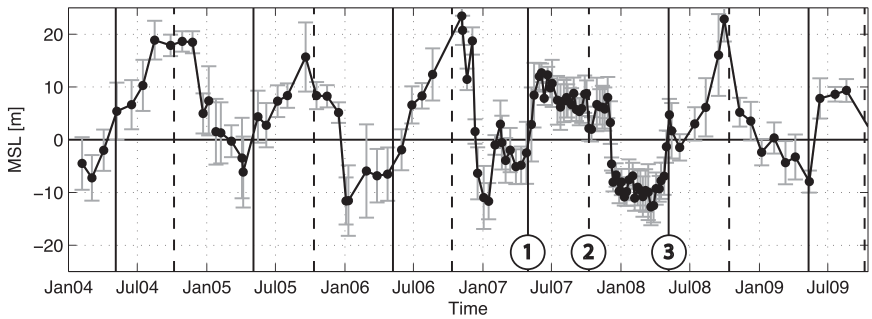

FIG. A1. Horizontal location of the MSL contour (mean removed) vs time at North Torrey Pines (see Fig. 1) for ~6 years. Alongshore mean (black curve) and scatter bars (±1 std dev) are shown. Vertical black lines indicate San Diego County bathymetry survey dates (winter is solid; summer is dashed). Surveys discussed in the appendix text, May 2007, October 2007, and May 2008, are labeled 1, 2, and 3, respectively.

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