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Rip currents, mega-cusps, and eroding dunes

E.B. Thornton [a,*], J. MacMahan [a], A.H. Sallenger Jr. [b]

[a] *Oceanography Department, Naval Postgraduate School, Monterey, CA 93943, United States*
[b] *Center for Coastal Geology, U.S. Geological Survey, St. Petersburg, FL 33701, United States*

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Abstract

Dune erosion is shown to occur at the embayment of beach mega-cusps O(200 m alongshore) that are associated with rip currents. The beach is the narrowest at the embayment of the mega-cusps allowing the swash of large storm waves coincident with high tides to reach the toe of the dune, to undercut the dune and to cause dune erosion. Field measurements of dune, beach, and rip current morphology are acquired along an 18 km shoreline in southern Monterey Bay, California. This section of the bay consists of a sandy shoreline backed by extensive dunes, rising to heights exceeding 40 m. There is a large increase in wave height going from small wave heights in the shadow of a headland, to the center of the bay where convergence of waves owing to refraction over the Monterey Bay submarine canyon results in larger wave heights. The large alongshore gradient in wave height results in a concomitant alongshore gradient in morphodynamic scale. The strongly refracted waves and narrow bay aperture result in near normal wave incidence, resulting in well-developed, persistent rip currents along the entire shoreline.

The alongshore variations of the cuspate shoreline are found significantly correlated with the alongshore variations in rip spacing at 95% confidence. The alongshore variations of the volume of dune erosion are found significantly correlated with alongshore variations of the cuspate shoreline at 95% confidence. Therefore, it is concluded the mega-cusps are associated with rip currents and that the location of dune erosion is associated with the embayment of the mega-cusp.

Keywords: rip currents; mega-cusps; dune erosion; waves; morphodynamics; hot spots

1. Introduction

The shoreline of southern Monterey Bay is one of the world's best examples of a quasi-stable rip current system owing to abundant sand supply and near normal wave incidence. Rip channels are persistent morphologic features, which are evident in the photograph (Fig. 1) taken atop a 35 m high dune along the shoreline in southern Monterey Bay. Large beach cusps, termed mega-cusps, with alongshore lengths O(200 m) are also evident.

A convenient morphodynamic framework is provided by Wright and Short (1984), who characterize beach states using a dimensionless fall velocity ($W=H_b/Tw_s$, where H_b is breaking wave height, T is wave period and w_s is sediment fall velocity) starting with high energy dissipative beaches ($W>6$), to intermediate ($5>W>2$), and lower energy reflective beaches ($W<1$). Given the nominal range of H_b (1–4 m), T (8–16 s) and grain size (0.2–1.0 mm), the most common beach state is intermediate, which is further subdivided into alongshore bar–trough beach, rhythmic bar and beach, transverse bar and beach, and low-tide terrace beach. The values of W range from 0.5 to 5 for southern Monterey Bay,

* Corresponding author. Tel.: +831 656 2847; fax: +831 656 2712.
E-mail address: thornton@nps.edu (E.B. Thornton).

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Fig. 1. View looking north from a dune crest at Fort Ord showing large scale O(200 m) cuspate shoreline with rip currents (indicated by arrows) at the center of their embayment backed by high dunes (exceeding 40 m) vegetated by ice plant.

which increase from south to north as do the wave height and grain size, so that the various beach states tend to be distributed alongshore. The dominant beach morphologies are: 1) low-tide terrace incised by rip channels, 2) transverse bars with associated rip channels, and 3) crescentic, or rhythmic, bar and beach.

Wright (1980), Short and Hesp (1982) and others observed that erosion of intermediate beaches are dominated by the presence of rip currents, with the maximum erosion occurring in the lee of the rip current creating a mega-cusp embayment. If mega-cusps are erosion features of rip currents, this suggests rip currents initiate the morphology and determine the alongshore length scale. Therefore, to understand the alongshore length scale of the mega-cusps, it is essential to understand the mechanism(s) that form rip currents.

Quasi-periodic spacing of rip currents/channels has been observed at numerous locations around the world. Short and Brander (1999) combined observation of rip spacing from a wide variety of sites in Australia, Europe, the United States, Japan, South Africa, and New Zealand. They found the mean number of rips per kilometer ranged from 2 to 13 with the number generally decreasing with increasing wave height and wave period.

Breaking wave patterns in aerial photographs and video time-lapse images can be used to identify rip channels. Wave breaking is a function of depth (Thornton and Guza, 1981). Waves break continuously across shoals owing to shallower water depths, and shows up as white in aerial photos or video images owing to foam and bubbles generated during breaking. Wave breaking is delayed in deeper rip channels, which shows up as darker regions owing to a lack of wave breaking. Long-term monitoring of nearshore morphology with high spatial and temporal resolution has become possible with the application of video imaging (Lippmann and Holman, 1990). Video "time stacks" have proven a useful means of examining the evolution of nearshore morphology and rip channels (e.g., Holland et al., 1997; Van Ekenvort et al., 2004). Symonds and Ranasinghe (2000) used an alongshore line of time-averaged pixel intensity within the surf zone to identify rip channels as troughs in the intensity. Holman et al. (2006) examined 4 yr of daily time-averaged images. Of particular interest were the events when the rip channels were destroyed and their subsequent regeneration (termed "resets"). The average lifetime of individual rip channels for this pocket beach was 46 days. Resets were hypothesized to be due to filling in of channels during storm events by alongshore sediment transport.

A comprehensive rip current experiment in southern Monterey Bay, RIPEX, was conducted to measure their dynamics and kinematics (MacMahan et al., 2004, 2005, 2006). It became obvious in the course of the investigations on rip currents that observed cuspate shoreline and dune erosion had similar alongshore length scales with the rip channels, and that they behaved in similar manners in response to the wave climate. An aerial photograph mosaic of the 18 km shoreline from Monterey to the Salinas River shows rip channels all along the shore with increasing alongshore spacing toward the north (Fig. 2). A detailed aerial photograph (Fig. 3) shows that the shoreline is cuspate, and that a rip channel is located at the center of the embayment of all the mega-cusps.

Based on these qualitative observations, it is hypothesized that dune erosion occurs at the embayment of O (200 m) mega-cusps (Short, 1979; Short and Hesp, 1982; Shih and Komar, 1994; Revell et al., 2002) that are erosion features of rip currents (Bowen and Inman,

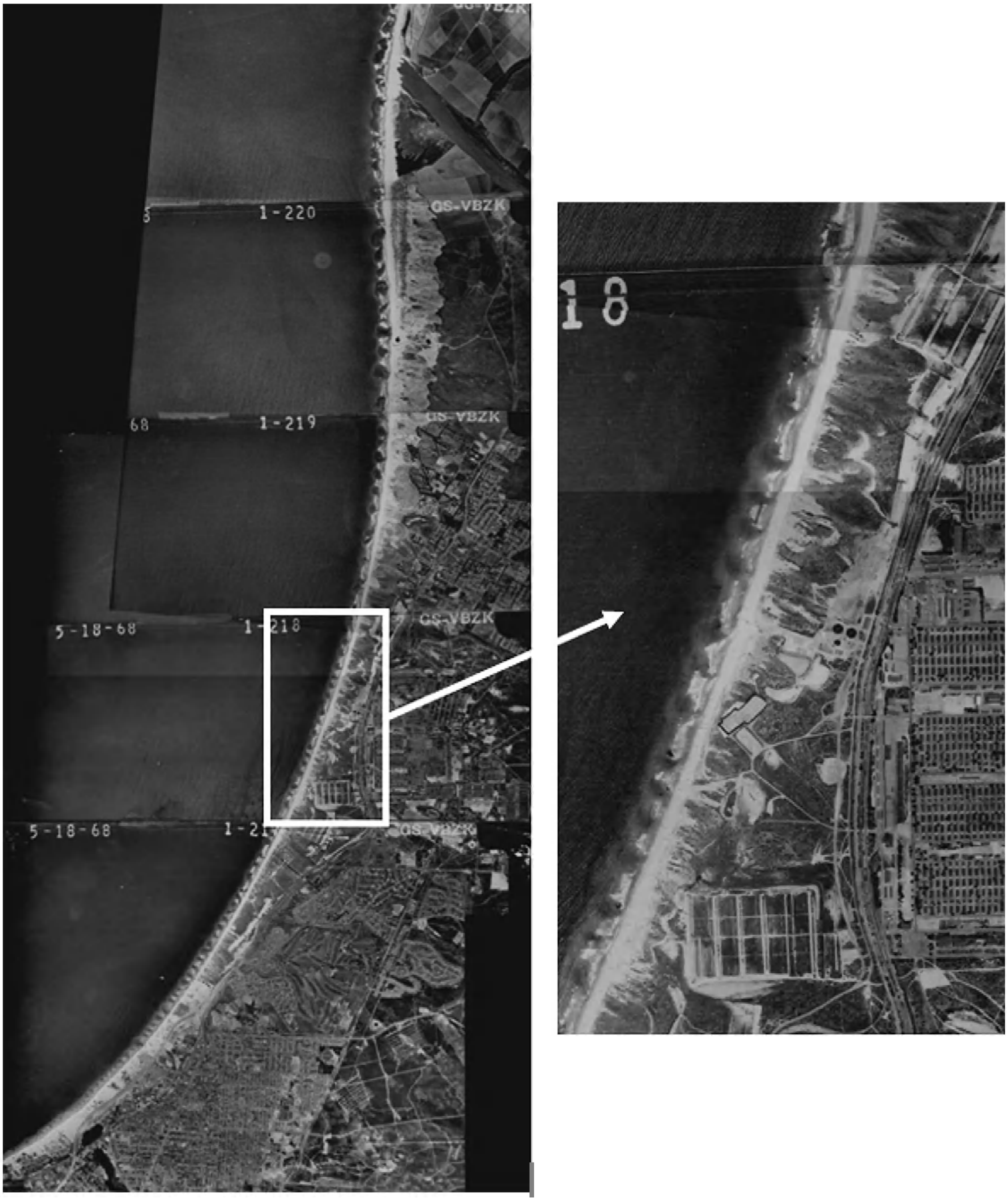

Fig. 2. 15 km aerial photo mosaic of southern Monterey Bay shoreline, which shows rip channels (dark region between white of breaking waves) with spacing increasing from north to south.

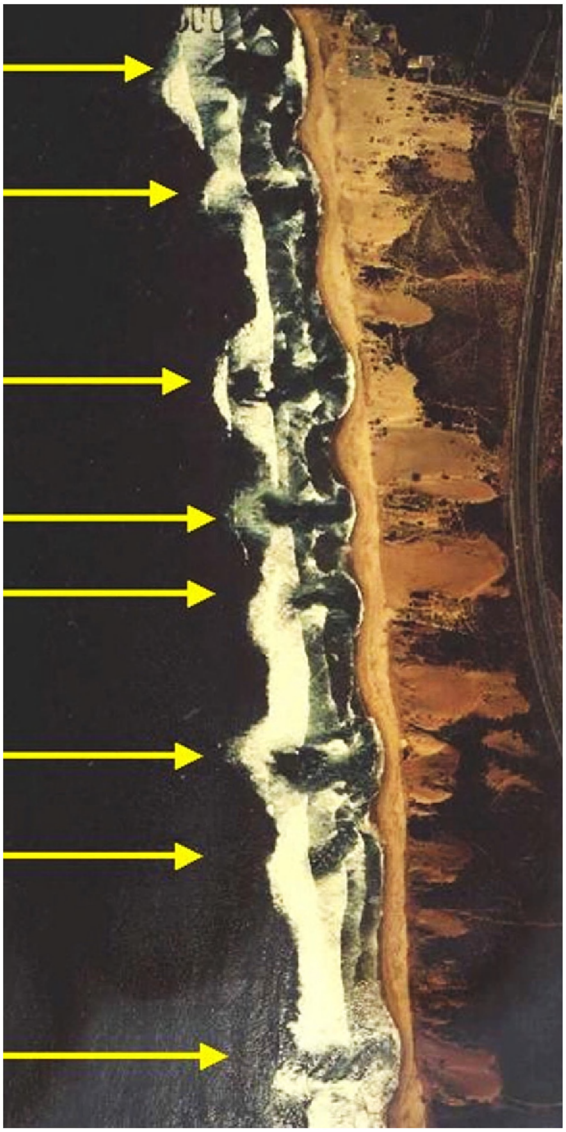

Fig. 3. Cuspate shoreline (wave lengths 100–400 m) with rip currents (dark areas in surf zone indicated by arrows where waves do not break in the deep rip channels) at the center of each mega-cusp embayment.

1969; Komar, 1971; Short and Hesp, 1982). The beach is the narrowest at the embayment of the mega-cusps where the natural buffer by the beach to erosion is decreased. This allows the swash and the additional set-up by large storm waves during coincident high tides to more easily reach the toe of the dune and undercut it, causing the dune to slump onto the beach. These hypotheses are tested by analyzing field measurements of rip channels, beaches and dunes acquired using a variety of surveying techniques, and of directional wave data acquired during the same time.

2. Setting

Monterey Bay is a 48 km long bay extending from Point Santa Cruz in the north to Point Piños in the south. Dominant bathymetric features within the bay are the Monterey Bay submarine canyon, the largest in the western hemisphere, and the ancient delta offshore the Salinas River (Fig. 4). The predominant deepwater wave directions are from west to northwest. The waves approach at near normal incidence all along the shore because of the narrowing of the aperture by the headlands to the north and south, the strong refraction across the canyon, and the historical (geologic time-scale) reorientation of the shoreline in response to the wave climate. The near-normal incidence of waves to the shoreline is conducive to rip current development, maintenance and relative stationarity.

The bay is partitioned into north and south littoral cells by the submarine canyon, which extends to the mouth of Elkorn Slough at Moss Landing. The submarine canyon intercepts the dominant littoral drift from the north and diverts it down the canyon. Wave refraction analysis by the U.S. Army Corps of Engineers (1985) over the bulge in the bathymetric contours about the ancient delta of the Salinas River suggests that the littoral transport diverges to the north and south at the river. This further subdivides the southern littoral cell into two cells at the river mouth.

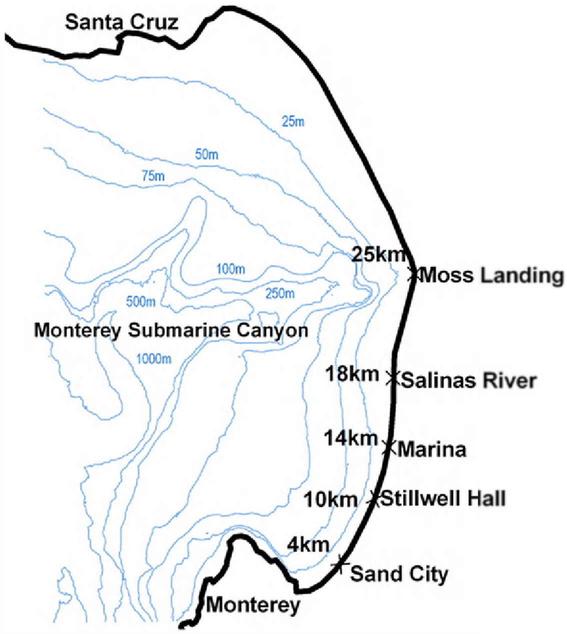

Fig. 4. Shoreline and bathymetry of Monterey Bay. The survey area is from Monterey to Salinas River (distances from Monterey are indicated in km).

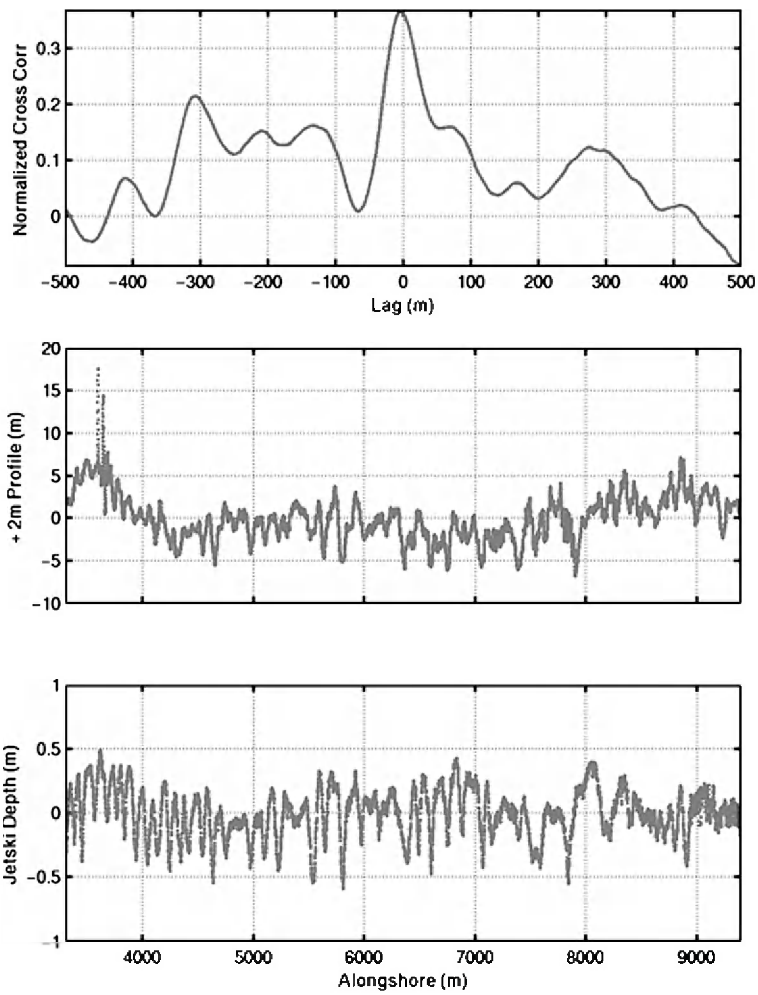

Fig. 5. The +2 m contour deviation from mean shoreline as a function of alongshore distance, 8 August 2003 (middle panel), shore parallel bathymetry showing shoals and rip channels alongshore on 18 July 2003 (bottom panel), and the cross-correlation between the two (upper panel).

The focus of this study is the littoral cell encompassing the 18 km shoreline from Monterey (0 km) to the Salinas River (18 km) (Fig. 4). The sandy shoreline is backed by extensive dunes, which between Sand City and Marina rise to heights exceeding 40 m. The shoreline and dunes are in a general state of erosion with average recession rates varying from 0.5 to 2 m/yr (Thornton et al., 2006). Erosion is episodic, and only occurs during coincident high tides and sustained storm waves. The tides are semi-diurnal with a mean range of 1.6 m. Sand size varies alongshore, dependent on wave height. The largest median grain size on the beach face ranges from 0.6 to 1 mm between the Salinas River and Fort Ord where the wave energy is the largest, and then decreases towards Monterey (Dingler and Reiss, 2001). Grain size and petrology evidence suggest that the sediment contribution by the Salinas River to the south even during times of major floods is small and limited to within 7 km of the river mouth (Clark and Osborne, 1982). Therefore, sand slumping onto the beach due to erosion of the dunes is the primary source of sediments to the southern littoral cell. Alongshore variation in long-term (averaged over ~40 yr) erosion appears correlated with the alongshore variation in mean wave energy (Thornton et al., 2006).

3. Field measurements

3.1. Morphology

The rip channel/shoal morphology, cuspate shoreline and dune erosion are measured using a variety of survey techniques. Bathymetry is measured by a sonar mounted on a personal watercraft (PWC) navigated using

Kinematic Differential GPS (KDGPS) with an ~5 cm rms accuracy in all three directions sampling at 10 Hz (MacMahan, 2000). On a low wave day (<~50 cm wave height), the personal watercraft was piloted along a line maintaining a constant distance of approximately 25 m from shore. The resulting measurements resolve bar shoals and rip channels continuously alongshore (Fig. 5, bottom panel), from which rip channel spacing can be determined.

The cuspate shoreline is determined by measuring the +2 m contour using an all-terrain vehicle (ATV) navigated with KDGPS. The ATV drives the beach at low tide close to the water line and returns higher on the beach. The 2 m contour is interpolated from the location information of the two lines. The 2 m contour is chosen as it includes the classic (O(30 m)) beach cusps, which are not present below mean sea level (MSL) and are not generated on the back beach. The +2 m contour is higher than the mean high-high water (MHHW) elevation of +0.8 m relative to MSL. The curvature of the mean shoreline is subtracted from the surveys. A mean shoreline of the measured 18 km shoreline on 7 January 2004 was obtained by fitting six contiguous least-square-fit quadratic sections that are joined by matching intersections and slopes. This mean shoreline is subtracted off all measured beach surveys (e.g., Fig. 5, middle panel). The beach surveys were started in July 2003, but only measured sporadically until February 2004, after which surveys have been conducted O(every 2 weeks) to obtain a time history of the mega- and beach cusp evolution.

The shoreline of Monterey Bay was surveyed using airborne Light Detection and Ranging (LIDAR) before (October) and after (April) the 1997–1998 El Niños winter, during which time significant erosion of the beaches and dunes occurred (up to 15 m dune recession).

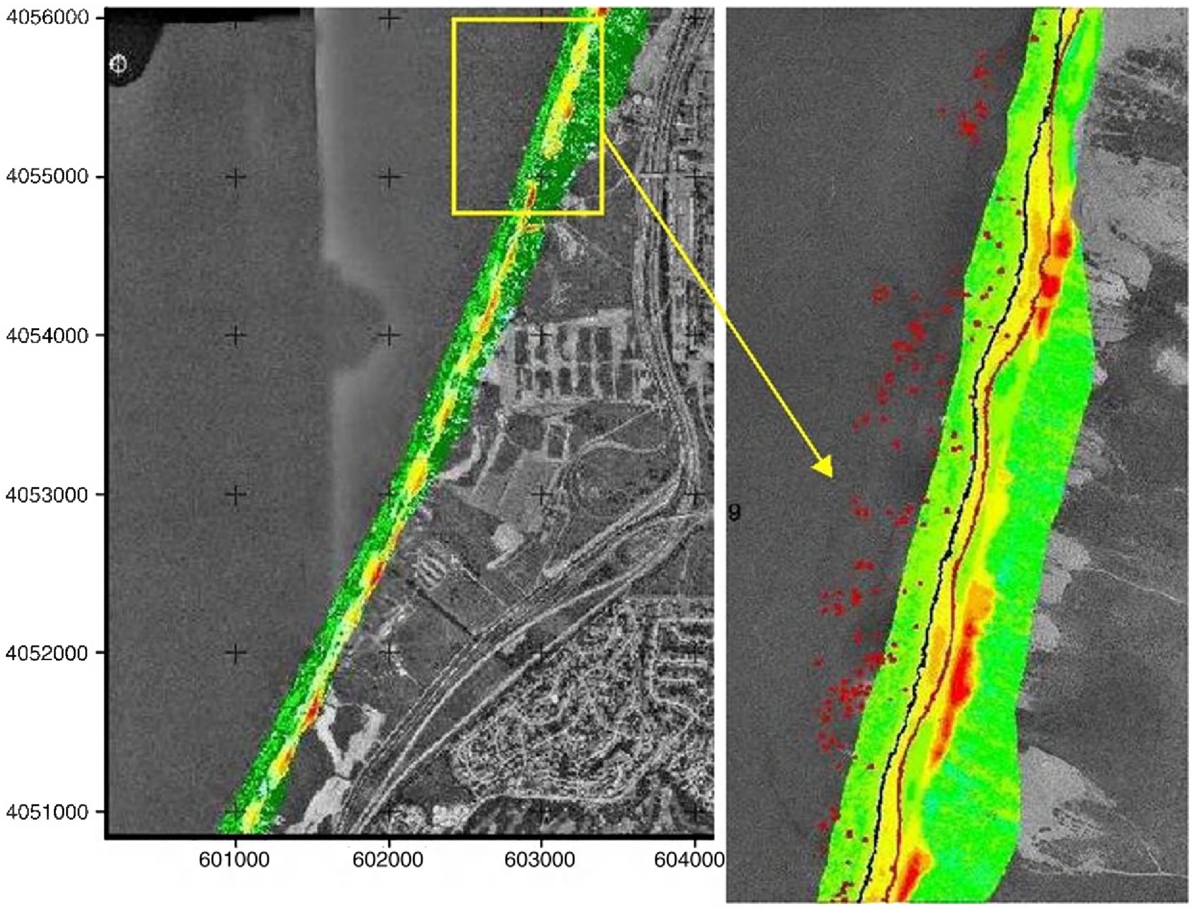

Fig. 6. Elevation differences between LIDAR surveys obtained October 1997 and April 1998 along 4 km of shoreline showing “hot spots” of erosion (red) spaced 100–400 m alongshore. Inset blow-up shows +2 m beach contours for October 1997 (black) and April 1998 (red). Hot spots occur at embayment of mega-beach cusps.

The LIDAR measures the subaerial topography of the exposed beach and dunes with 1–2 m horizontal resolution with better than 15 cm vertical accuracy (Sallenger et al., 2003). Erosion is determined from the difference of the two surveys. Large alongshore variations of the dune erosion were measured (Fig. 6), which shows up as "hot spots" with length scales of 200–500 m. The +2 m beach contour measured by LIDAR for both pre- and post-El Niño is indicated in the Fig. 6 inset, which shows large cuspate features having the same 200–500 m length scale as the dune hot spots. The dune erosion most commonly occurs in back of the mega-cusp embayments where the beach width is the narrowest.

To quantify the randomly sampled LIDAR data, the measurements were converted to a regular grid in rectangular coordinates using a Delany triangulation interpolation. Cross-shore profiles were computed every 25 m alongshore. Beach and dune erosion are determined by subtracting the cross-shore profiles of April from that of October (Fig. 7). The dune toe height, determined from where there is a large change in profile slope, divides the beach from the dune profile.

The magnitude of the beach and dune erosion variability is examined by comparing four cross-shore LIDAR profiles for 1997 and 1998 spaced ~100 m apart, starting at alongshore location 11.5 km and proceeding north (Fig. 8). The first panel shows beach profiles with no dune erosion, 100 m north both beach and dune erosion occur with 14 m of dune recession, 100 m farther north there is again beach erosion with no dune erosion, and 100 m farther north there is 11 m of dune recession with no beach erosion. As will be shown, this large alongshore variation in dune erosion is related to the cuspate shoreline, which is related to the rip currents.

3.2. Waves

Directional wave spectra are measured routinely at NOAA 46042 buoy located 40 km offshore of Monterey Bay and are refracted shoreward (Fig. 9) to provide wave heights throughout the bay every 4 h (http://cdip.ucsd.edu/models/monterey). Nearshore directional wave spectra are measured by acoustic Doppler current profilers cabled to shore located in 12 m offshore of Monterey and Sand City, and by a Wave Rider directional buoy in 17 m offshore Marina. There is a large gradient in wave height over km scales going from small waves in the shadow of the southern headland, to the middle of the bay at Fort Ord and Marina where convergence of waves owing to refraction over the Monterey Bay submarine canyon results in increased wave heights.

Frequency-directional spectra of the incident waves at the shallow water locations are calculated from the time series of pressure and velocity, and slope and heave using a Maximum Entropy Method (Lygre and Krogstad, 1986) every 2 h. The significant wave height

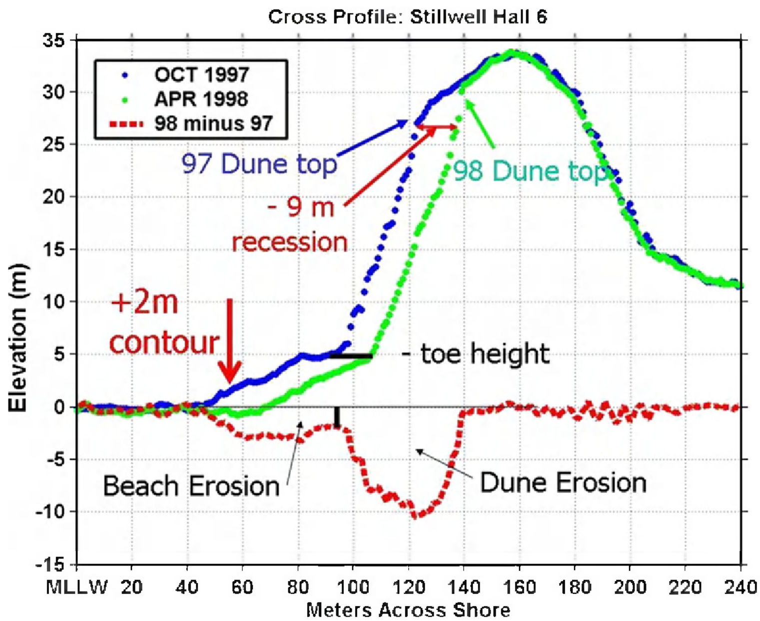

Fig. 7. Cross-shore profiles as measured by the LIDAR surveys for October 1997 and April 1998. Beach and dune erosion separated by the toe height are determined from the difference of the two profiles. The 2 m contour is determined from the profile.

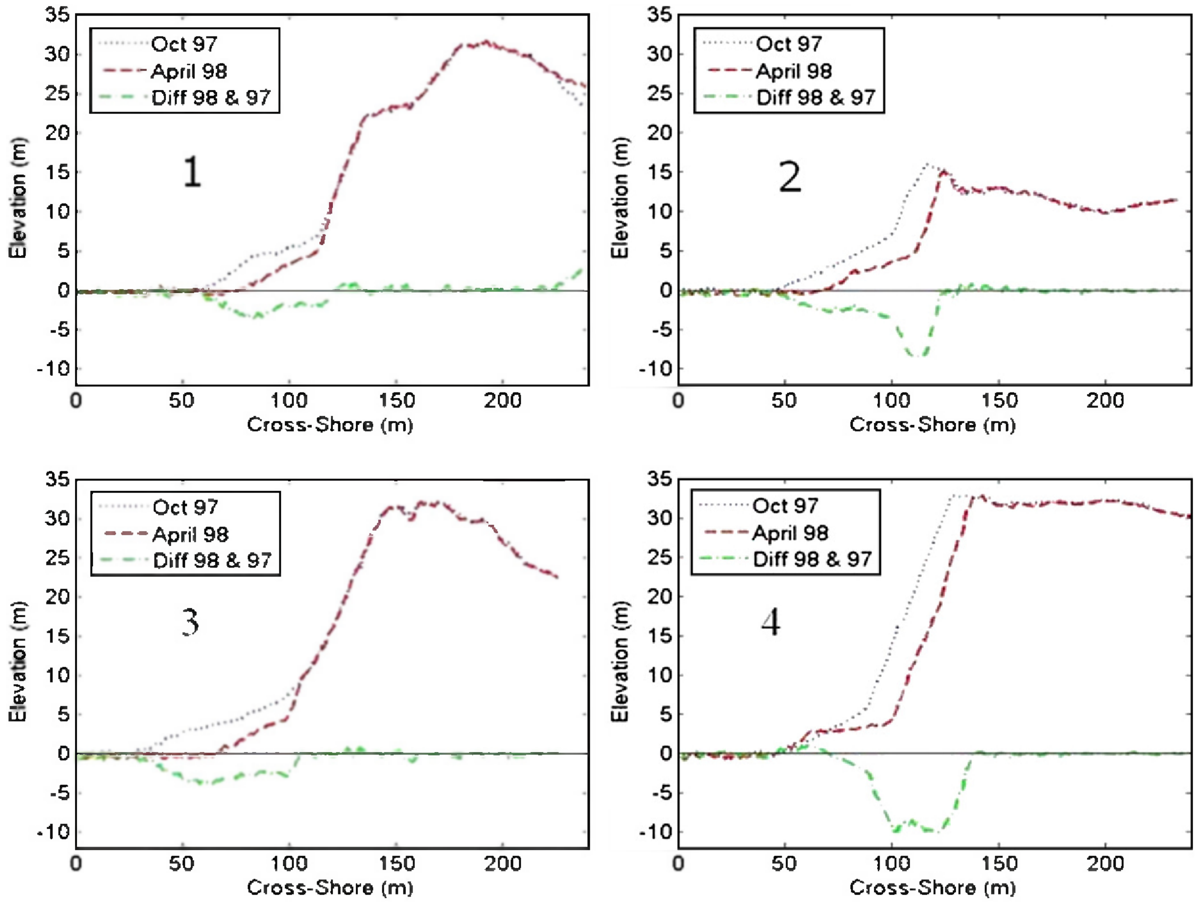

Fig. 8. Cross-shore profiles spaced approximately 100 m in the alongshore as determined from the LIDAR surveys showing large alongshore variations is beach and dune erosion.

(H_s), peak period (T_p), and mean wave direction of peak period (D_p) at Sand City in 12 m water depth are compared with data from the offshore buoy for January–April 2004 in Fig. 10. H_s at 12 m depth reflects the offshore H_s in time with diminished heights. The D_p during this time was primarily from the west-northwest to south (the shoreline orientation of 313° has been subtracted). Owing to wave refraction, the mean wave approach direction in shallow water is near normal incidence. The peak periods of waves measured in shallow water are longer than measured offshore at the buoy (not shown). The wave energy inside the bay represents the swell component of the wave spectrum as refraction and the narrower aperture of the headlands filter the higher frequencies associated with diurnal sea breezes.

4. Analysis of data

The alongshore spatial and temporal variations of rip channel, mega-cusp, and dune recession spacings are cross-correlated with each other to test hypotheses. It was not possible to acquire synoptic data on rip channels, cuspate shorelines and dune erosion owing to the episodic occurrences of the dune erosion. Many years there is no dune erosion. Dune erosion is enhanced during El Niños winters when storm waves occur more frequently with greater intensity on average. El Niños winters occur on average about every 7 yr, and one has not occurred since starting the beach surveys. Therefore, the rip channel variations obtained from an opportunistic PWC survey obtained when the waves were low are compared with the cuspate shoreline surveyed with KGPS-equipped ATV, and then the cuspate shoreline and dune erosion measured with LIDAR are compared for different times.

The hypothesis that the mega-cusps are associated with rip currents is examined first by cross-correlation of the shore-parallel PWC survey of bathymetry conducted on 8 August with the +2 m contour determined by an ATV survey on 18 July 2003 (Fig. 5). The

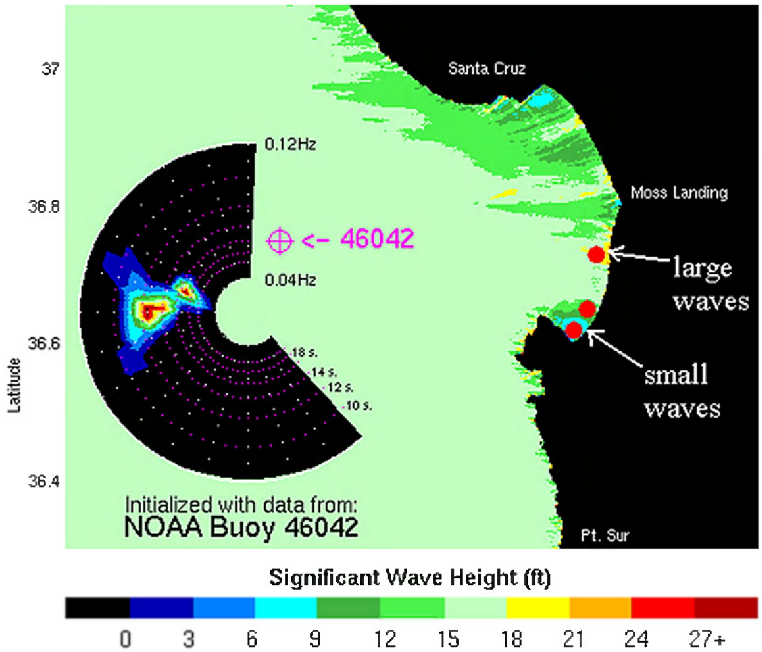

Fig. 9. Directional wave spectrum measured at NOAA buoy 46042, 40 km offshore, refracted into Monterey Bay. Large variations of wave height occur alongshore owing to wave refraction over the Monterey Bay submarine canyon and sheltering by headlands. Locations of nearshore directional wave sensors are indicated by dots.

spacing of the rip channel locations and mega-cusps of the shoreline varied between 200 and 300 m over the approximate 6 km of shoreline. The maximum cross-correlation value between the rip channel morphology and shoreline is 0.35, which is significant at the 95% confidence level with near zero spatial lag.

The lack of correlation (value$<$1) between the two records occurs primarily because of the 21-day separation time between surveys. This is demonstrated by calculating de-correlation times and migration rates from cross-correlations of the shoreline spatial series. The shoreline spatial series for February– April 2004 when surveys were taken regularly is used. A reference +2 m contour shoreline at the start of the series on yearday 51 (20 Feb 05) is cross-correlated with subsequent shoreline surveys. In addition, a single shoreline survey taken 44 days previous (on yearday 10) to the reference survey is cross-correlated (Fig. 11). Since the shoreline series is inhomogeneous (scale varies alongshore owing to wave height gradient), the cross-correlations are done for sections of shoreline. As an example, cross-correlations for the shoreline between 4 and 10 km show the peak correlation decreases with time and the location of the maximum correlation shifts alongshore indicating the cusps are migrating alongshore (Fig. 12). The peak correlation as a function of time since the initial survey is fitted with an exponential curve in a least-square sense (Fig. 12, left panel). A measure of the de-correlation time is the e-folding time. Both the previous (indicated by a circle) and subsequent shoreline surveys (stars) are consistent. The e-folding time during "normal" winter/spring waves exceeded 50 days.

The de-correlation with time is used to explain the lack of correlation between the mega-cusps and rip channels shown in Fig. 5. If the rip channel morphology and shoreline act in the same temporal manner (i.e., correlated), then the expected cross-correlation with a 21-day separation in time using the de-correlation with time measured above would be 0.65. If it is assumed the rip channel morphology and shoreline act independently with time, then the expected cross-correlation with a 21-day separation in time using the de-correlation with time of 0.65 would be the square of that value to give 0.4, which is consistent with the measurements.

Mean migration rates of the mega-cusps for sections of shoreline are determined by the displacement of the peak correlation with time (Fig. 12, right panel). For the 4–10 km section of beach, the mega-cusp system migrated at 3.4 m/day to the north for 70 days from 7 January to 18 March. Since the shoreline and rip channel bathymetry are correlated and it is assumed the cuspate

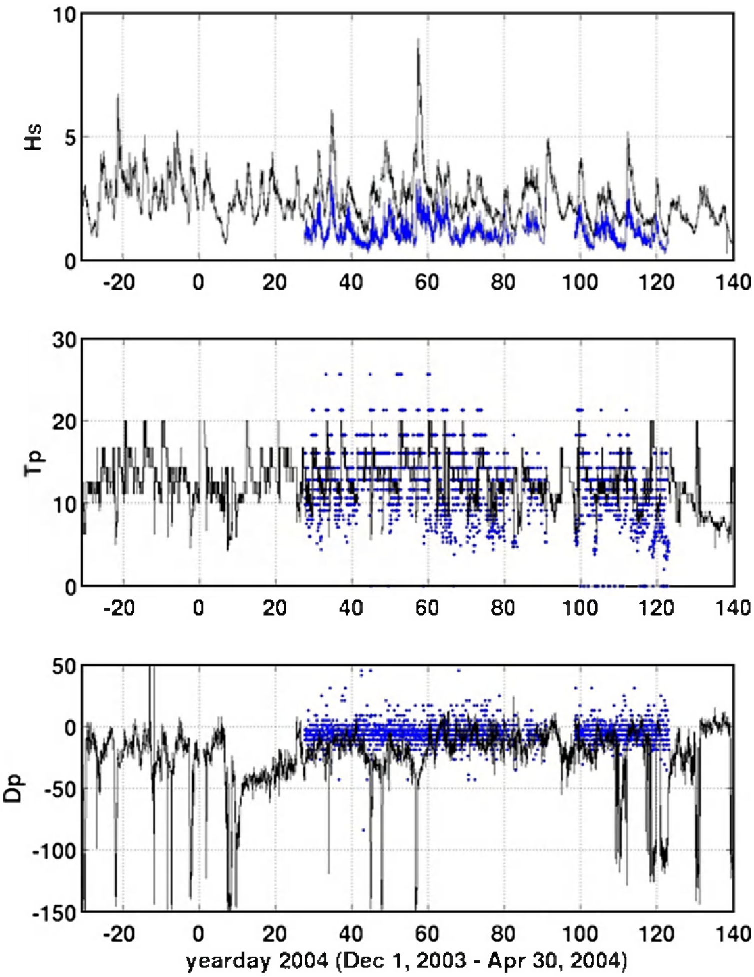

Fig. 10. Significant wave heights, H_s, at offshore buoy and at 12 m depth at Sand City, California, peak wave period at 12 m depth, T_p, mean wave direction at peak period, and D_p, at the offshore buoy (solid black line) and at 12 m depth (blue dots) relative to shore normal.

shoreline is an erosion feature of the rip currents, it would be expected that the rip channels migrate at the same mean rate. Therefore, it would be expected that the spatial lag for their cross-correlation would be near zero as they migrated together at approximately the same rate as is found in Fig. 5.

For the 10–15 km section of shoreline, the de-correlation e-folding time is approximately 40 days (Fig. 13, left panel). This section of beach is more exposed to higher waves, and this may account for the faster de-correlation time compared with the section of shoreline between 4 and 10 km. The mega-cusps migrated at 3.7 m/day to the north for 70 days from 7 January to 18 March, and then were stationary (Fig. 13, right panel), similar to the migration of the mega-cusps between 4 and 10 km.

The 40–70-day de-correlation times imply that bi-monthly surveys are sufficient to avoid aliasing the time series and for describing the processes. However, between shoreline surveys on 9 December 2003 to 7 January 2004, a major storm occurred (7 m significant wave height offshore on 10 December during time of spring tides, see Fig. 10) and the de-correlation time was less than the time between surveys (Fig. 14). It is noted that the largest waves of the winter (>8 m) occurred on 1 March during a time of neap tides such that little or no erosion occurred, and the shoreline correlation did not change between surveys (Fig. 13, left panel). The ATV surveying system was not operational from the last survey in April until the next survey in October, a 190-day time period. However, the two surveys were still correlated, indicating that the de-correlation time during the summer months when the waves were lower exceeded 200 days (Fig. 14).

The hypothesis that dune erosion occurs at the embayment of the mega-cusps is examined by cross-correlating the alongshore variation of dune erosion

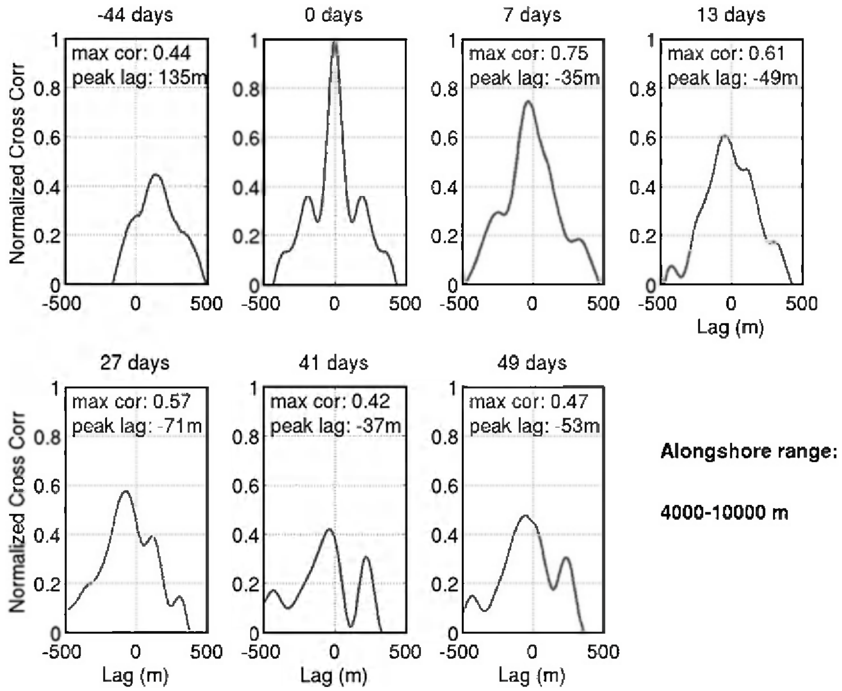

Fig. 11. Cross-correlations between shoreline survey of +2 m contour for 4–10 km on 20 February 2004 and subsequent surveys. Days between survey and survey on 20 February 2004 is noted at top of each plot.

with the +2 m beach contour. The volume of dune erosion was determined by the difference between cross-shore profiles every 25 m for the 1997 and 1998 LIDAR surveys. The cuspate shoreline was determined from the 2 m contour measured from the cross-shore profiles every 25 m for the 1998 LIDAR survey. The dune erosion and the alongshore variations in the shoreline 2 m contour are significantly correlated at 95% confidence (Fig. 15, upper panel).

Since dune erosion is found significantly correlated with beach width, which is narrowest at the embayment of mega-cusps, it is expected that the dune erosion would be in-phase with the shoreline, *i.e.* zero spatial lag. However, a significant spatial lag of about 75 m is noted between the volume of dune erosion and the mega-cusps, which is discussed in the next section.

Both the cross-shore width of the mega-cusps (measured as the difference between the cross-shore locations of the horn and embayment) and the alongshore mega-cusp length varied alongshore. For example during the April 1998 LIDAR survey, widths of the cusps increased from 10 m to more than 40 m and lengths increased from 180 m to over 400 m proceeding from south to north (Fig. 15, middle panel). The volume of dune erosion also

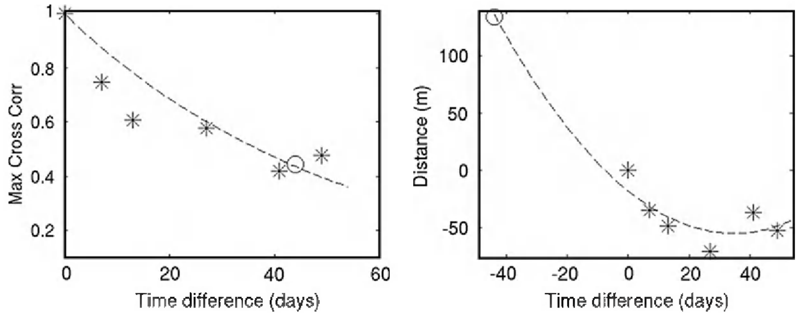

Fig. 12. Maximum cross-correlation between 20 February 2004 and subsequent (*) and previous (O) surveys (left panel), and the displacement of the maximum cross-correlation between subsequent surveys describing migration of shoreline (right panel) for 4–10 km.

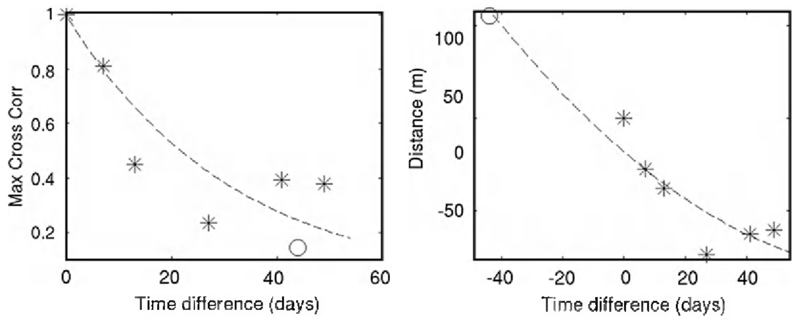

Fig. 13. Maximum cross-correlation between 20 February 2004 and subsequent (*) and previous (O) surveys (left panel), and the displacement of the maximum cross-correlation between subsequent surveys describing migration of shoreline (right panel) for 10–15 km.

varies significantly alongshore (Fig. 15, lower panel) and is dependent on both recession rate and height of the dune.

5. Discussion

5.1. Spatial lag between dune erosion and mega-cusps

Since the enhanced dune erosion remained in the same locations after the 1997–1998 El Niño winter, the spatial lag that was measured between the dune erosion and 2 m contour is due to the migration of the cusps between the time(s) of the dune erosion and the April shoreline survey. Dune erosion is the culmination of storm events over the winter. A measure of erosion potential is when swash run-up exceeds the elevation of the toe of the dune, so that the swash can impact the dune. Following the method by Sallenger et al. (2000), the swash run-up height of the average highest 2% waves (Holman and Sallenger, 1985; Holman, 1986) is calculated based on wave height and period of waves measured every 4 h at NOAA deep water direction wave buoys:

$$R_{\mathrm{u}} = H_0\left(\frac{0.83\tan\beta}{\sqrt{H_0/L_0}} + 0.2\right) + \eta_{\mathrm{tide}}$$

where H_0 is significant wave height in deep water, L_0 is deep water wave length calculated from the period using linear wave theory, $\tan\beta$ is the beach slope and η_{tide} is the tide elevation measured in Monterey Bay at the time of the wave measurement.

The NOAA wave buoy 46042 offshore Monterey Bay failed on 27 October 1997 owing to large waves and was not restored until June 1998, so these data were not available during the time of interest. Instead, the waves measured by the NOAA wave buoy 46026 off San Francisco 110 km to the north were used during 1997 and when it also failed in early January 1998, the NOAA wave buoy 46014 off Mendocino 310 km to the north was used. The wave heights and periods measured by the northern buoys were "adjusted" to correspond to the Monterey buoy data by using linear regression curves between buoys calculated for a 130-day period (19 June–26 October 1997). The waves at Monterey during this time period were 1.14 times greater than off San Francisco, but 0.94 times less than off Mendocino. The mean peak wave period at Monterey was 2% greater than off San Francisco and 8% greater than off Mendocino. The wave heights and periods in deep water off Monterey Bay and calculated run-up during the interval of LIDAR surveys are shown in Fig. 16. The horizontal dashed line is the mean elevation of the dune toe. The vertical solid lines are days when the LIDAR surveys were conducted. During the time between LIDAR surveys, the calculated run-up exceeded the dune toe for an extended time 40 to 90 days prior to the

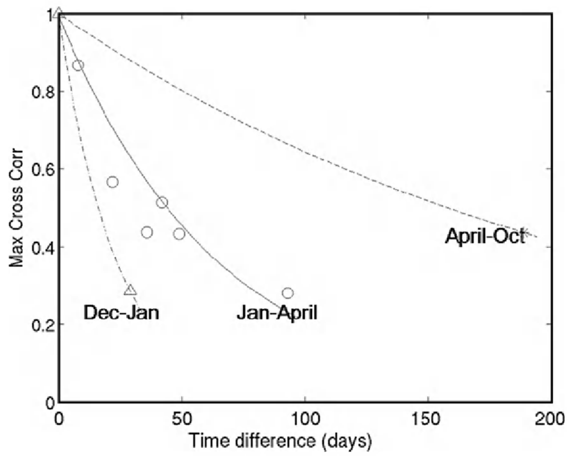

Fig. 14. De-correlation between surveys of +2 m contour for 10–15 km alongshore.

survey in April, when significant erosion would be expected. Given that the average cusp migration rates measured during the 2004 surveys ranged 0 to 3.5 m/day, the mega-cusps could easily be expected to have migrated 75 m between when the erosion occurred and the April LIDAR survey of the 2 m shoreline contour.

The lack of correlation (<1) between alongshore variations in dune erosion and the 2 m contour is assumed due primarily to the approximate 45-day time difference between the cumulative occurrence of dune erosion (latest time of when the persistent run-up exceeded the toe of the dune, Fig. 16) and when the 2 m contour survey was performed. Assuming that the shoreline migration acted independently after the occurrence of dune erosion, and using the measured correlation function between rip channel locations and 2 m contour as an analog (Figs. 12 and 13, right panels), the expected maximum correlation would be approximately 0.4, which is comparable to the measured value (Fig. 15, upper panel).

5.2. Hot spots

It has become apparent that erosion does not occur uniformly, but is highly variable with recognizable "hot spots" of erosion. Hot spots are sections of coast with substantially higher rates of erosion than adjacent areas. There are a number of processes responsible for hot spots, only some of which are understood (such as those associated with wave focusing around offshore holes or shoals). List and Farris (1999) used a GPS-equipped ATV to measure changes of mean high water shoreline position along a 70 km section of coastline on the Outer Banks of North Carolina and 45 km of Cape Cod, Massachusetts. They found "reversing storm hot spots", which are areas of significant storm erosion that alternate, on a spatial scale of 2–10 km, with sections of coast that experience little or no erosion. During post-storm fair weather, storm hotspot erosion is rapidly reversed by a similar magnitude of accretion, while the intervening areas remain unchanged. The cause of these hot spots is not understood.

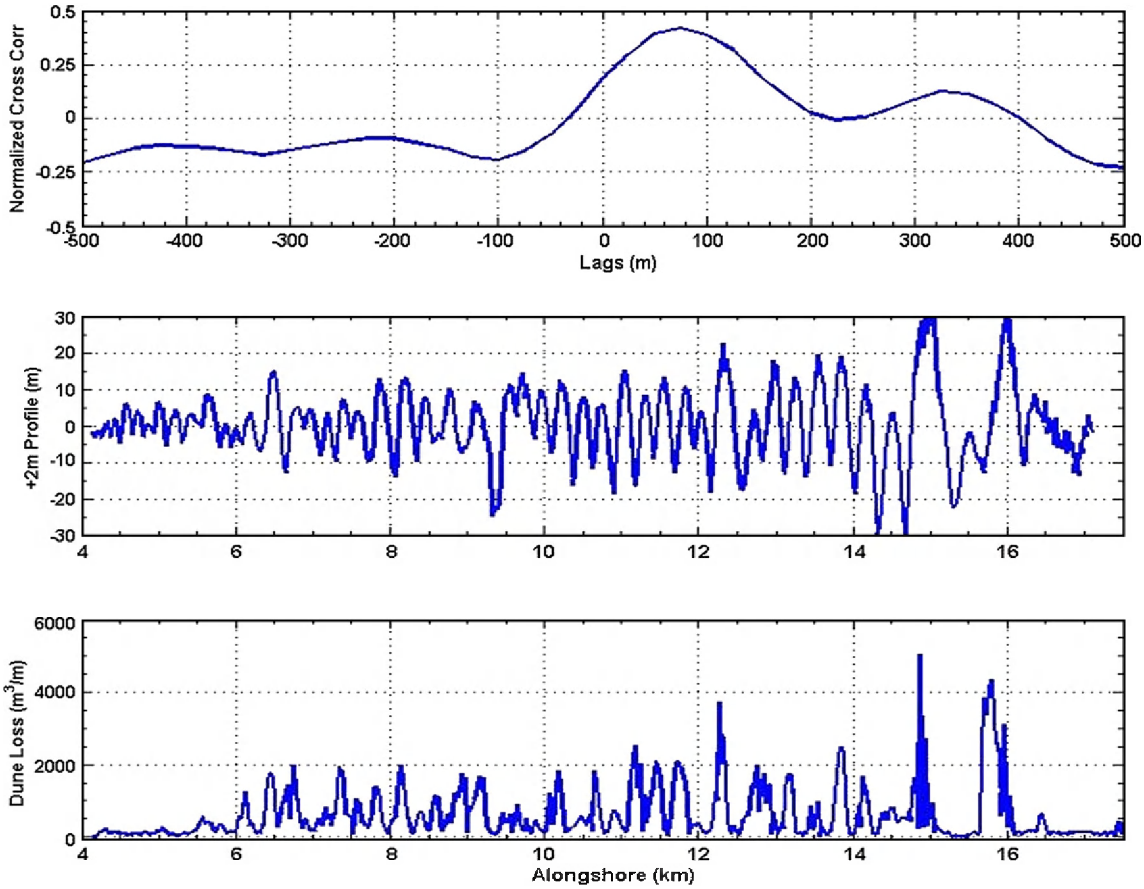

Fig. 15. Cross-correlation (top panel) between +2 m contour on April 1998 (middle panel) and volume of alongshore dune erosion between October 1997 and April 1998 (bottom panel) obtained from LIDAR surveys.

Hot spots observed in southern Monterey Bay are irreversible. Dune recession is permanent, because there is no present-day natural mechanism for the restoration of the dune face. Based on the analysis here, we feel that the hot spots are due to the narrowing of the beach at the mega-cusp embayments associated with rip currents making the dunes at these locations more vulnerable to undercutting by swash during coincident high tides and storm waves.

The spatially variable erosion created by these hot spots enhances the erosion rate as compared with a uniform shoreline with the same average beach width. For the uniform beach, a smaller percent of swash events would be able to reach to dune toe because of the greater beach width compared with the narrower beach in the embayment. Hence, fewer erosion events would occur with decreased overall erosion.

The location of these hot spots cannot persist, as eventually there would be substantial holes in the dune. The dunes are observed to recess quasi-uniformly over the long term. Therefore, the location of the rip channels and associated mega-cusps and dune erosion either migrate, or are "reset" and regenerated at random alongshore locations. The primary sediment supply to the littoral cell of southern Monterey Bay is the slumping of the sand onto the beach by the eroding dune. The dune slumping onto the beach can act as a negative feedback by providing a supply of sand to fill the cuspate shoreline and rip channel in the absence of alongshore currents.

It is important to remember that dune erosion occurs episodically and does not even occur every winter. Severe erosion occurred during the 1997–1998 El Niños owing to the large storm waves that persisted for extended periods of time (Fig. 16). The 1997–1998 El Niños along with that in 1982–1983 were the most extreme storms of the 20th century (Seymour, 1998), and the 1997–1998 El Niño caused the more severe erosion in southern Monterey Bay. Persistent, or repeated, storms cut back the beach, making the dunes more vulnerable to future storms. The total calculated

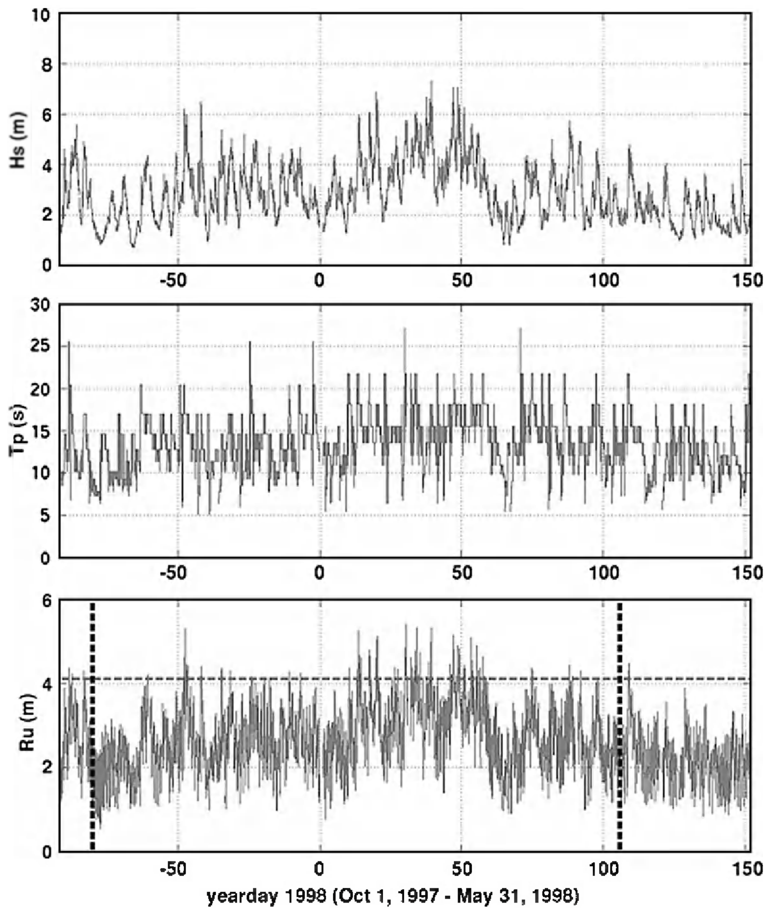

Fig. 16. Significant wave height, H_s, and peak wave period, T_p, at offshore buoys, and calculated run-up plus tide elevation (dotted line is mean elevation of dune toe). The vertical lines in the run-up plot are the times of the LIDAR surveys.

volume of dune erosion over the 18 km of shoreline during the 1997–1998 El Niño was 1,820,000 m^3, which is almost seven times the historical annual mean dune erosion of 270,000 m^3/yr (Thornton et al., 2006).

Hot spots are important to take into account in coastal management decisions. In the consideration of setbacks, it is important to recognize that there is a significant variation, both in space and time, in the mean erosion rate associated with potential hot spots. Hot spots often cause property owners to panic, and seek to armor their property. In the case of southern Monterey Bay, the hot spot are not expected to return at the same location the next year.

Interestingly, reversing hot spots have only been recorded on the eastern shoreline of the U.S., while cuspate shorelines associated with rip currents are most commonly observed on the west and gulf coasts. This is presumably associated with the differences in wave climate.

5.3. Morphodynamics

Migration of rip channels and their time-scales are not understood. Obviously at some locations alongshore currents and associated littoral sand transport cause rip currents to migrate, but at the same time they act to destroy the rip channels by filling them. Alongshore currents are weak in southern Monterey Bay because of the near normal wave incidence (hence, the persistent rip fields). Local surfers observe (complain) that rip channels tend to be filled during large storms (therefore, diminishing their wave crest surfing edge). On the other hand, Dingler (pers. comm.), in the course of 17 yr of repeated beach profiles in Monterey Bay (Dingler and Reiss, 2001), visually observed that the rip channels tended to be filled by low, long-period summer waves transporting sand shoreward, which was also observed in a short-term field experiment by Brander and Short (2001). This process is not understood, and hopefully long-term video data will provide the necessary answers to this question.

Swash generated by incident and infragravity storm waves is responsible for undercutting the dunes at high tide. Swash is a function of the incident breaking waves. The interaction of the incident waves and outgoing rip current can cause waves to break, which would diminish the swash. Wave set-up (the mean of swash) in rip channels was measured in the laboratory by Haller et al. (2002). They found that set-up was dependent on how the waves broke within the rip channel. Higher set-up occurred when the waves did not break in the rip channel, but broke closer to the shoreline. No field data exists on swash in back of rip currents and only limited lab data is available. Therefore, the mechanism responsible for dune erosion in back of rip currents and in mega-cusp embayments is not well understood.

Haller et al. (2002) and MacMahan et al. (2006) found a counter circulation in back of the rip current near the beach that was created by an adverse pressure gradient as the waves broke closer to shore. The counter current may be important in eroding the embayment of the cusp in back of the rip current.

Classical beach cusps (wavelengths O(30 m)) were often observed to be well-developed with amplitudes increasing in the direction of increasing wave energy. Short (1999) suggests the beach cusps tend to occur on the mega-cusp horns, with a steeper eroded beach face in the embayment.

A deficiency in this study is that the data were not obtained synoptically. Dune erosion and a cuspate shoreline were measured using LIDAR and appear correlated. Unfortunately there were no aerial photos or time-averaged video images available during the time of the LIDAR surveys to establish a direct relationship between dune erosion, mega-cusps and rip channels. Four video camera systems have since been installed along the shoreline between Monterey and Marina, and future studies will address the temporal evolution of rip currents, cusps and dune erosion.

6. Summary and conclusions

Monterey Bay affords a natural laboratory to study rip currents, cuspate shorelines and eroding dunes. This study encompasses 18 km of shoreline in Monterey Bay, California. The bay consists of a sandy shoreline backed by extensive dunes, rising to heights exceeding 40 m. The shoreline and dunes are in a general state of erosion with average erosion rates varying from 0.5 to 2 m/yr. There is an increase in wave height going from small wave heights at the southern most part of the bay in the shadow of a headland, to larger waves in the center of the bay owing to convergence of waves by refraction over Monterey Bay submarine canyon. The waves approach at near normal incidence all along the shore, because of the narrowing of the aperture by the headlands to the north and south, the strong refraction across the canyon, and the historical (geologic time-scale) reorientation of the shoreline in response to the wave climate, resulting in well-developed rip currents and associated mega-cusps O(200 m) along the entire shoreline. The large alongshore gradient in wave climate results in a concomitant alongshore gradient in morphodynamic scale.

Dune erosion and shoreline morphology were measured using LIDAR during a time of high erosion (October 1997, April 1998). Temporal monitoring of the beach-face was performed O(every 2 weeks) by driving the beach with an ATV mounted with KGPS to determine the 2 m shoreline contour. Rip channels were surveyed by personal-water-craft equipped with sonar and KGPS. Directional wave spectra are measured in deep water and at three locations within southern Monterey Bay.

Enhanced dune erosion is shown to occur at the embayment of mega-cusps that are associated with rip channels. The beach is the narrowest at the embayment of the mega-cusps. This allows the swash of large storm waves during high tides to reach the toe of the dune, and undercut the dune causing it to slump onto the beach resulting in recession of the dune. The alongshore variations of the volume of dune erosion are correlated with alongshore variations of the cuspate shoreline at 95% confidence. Therefore, it is concluded the location of dune erosion is associated with the embayment of mega-cusps.

Rip currents are located at the center of mega-cusps. Rip current spacing and mega-cusps dimensions are the same. The alongshore variations of the cuspate shoreline are correlated with the alongshore variations in rip spacing at 95% confidence. Therefore, it is concluded the mega-cusps are associated with rip currents. The cuspate shoreline tends to be erased (straightened) by storms through both erosion of the horns and filling of the embayment. The slumping of the receding dune is the primary source of sand to the beaches. This source of sand is then available to build new mega-cusps.

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