El Niño and intertidal boulder field sedimentation at Point Reyes National Seashore

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ABSTRACT

Wave-exposed boulder fields, a common feature of the California coast, encounter drastic fluctuations in the amount of sand within them. This study examined the inter-annual and seasonal differences of sedimentation in an intertidal boulder field from September 2014 to March 2017. The study period included one El Niño winter, characterized by increased wave energy, and two ENSO-neutral winters. I used monthly photographs to qualitatively monitor sedimentation at two intertidal boulder fields in northern California. Sand depth was also measured within the boulder fields, and those measurements were positively correlated to the photographic assessments of sedimentation. Only one of the sites exhibited a strong seasonal cycle in sedimentation. Additionally, there were no differences in sedimentation between El Niño and ENSO-neutral winters. The results of this study indicate that sedimentation and erosion on beaches can vary dramatically between adjacent shorelines based on physical factors, such as exposure to swell conditions. Monitoring and understanding coastal sedimentation can inform land management decisions, marine resource reserves, and erosional processes during climate anomalies.

KEYWORDS

sand; beach morphology; wave energy; intertidal; seasonal; El Niño;

INTRODUCTION

Beach morphology can undergo drastic changes over time. Wave energy plays an important role in the transport of sediments and the transformation of sandy beach systems (Moore et al. 1999; Charlier et al. 1998; Cooper et al. 2013). Many regions of the California coast are exposed to wave energies that are produced from storms formed in the southern and northern hemispheres of the Pacific Ocean. Regions of a beach where sand is excavated leaves sea cliffs vulnerable to wave attack and susceptible to erosion (Sallenger et al. 2002). Accelerating coastal erosion rates and a rise in sea level in California raise many concerns when considering our heavily developed coast and the cultural and economic importance of its beaches. Long-term shoreline retreat, caused by episodic large wave events, can threaten infrastructure such as public facilities and coastal communities (Griggs & Johnson 1979; Flick 1994). Additionally, coastal areas are important habitat for a variety of organisms whose persistence can be threatened by inundation and erosion of sand (Garner et al. 2015). The transport of sediments and its impact on coastal habitats and infrastructure differ depending on a regions exposure to swell.

Seasonal differences in swell energy and direction play a key role in moving sediments and changing beach morphology. It is common for the coastline of California to experience larger waves in the winter than in the summer (NOAA, http://www.ndbc.noaa.gov/). In the winter, large swells originating in the north are responsible for decreases in beach width and height, while in the summer, small swells originating in the south result in increased beach width and height (Masselink & Short 1993). The energy transported by an ocean wave can be described, in part, by its height and period. A longer wave period, or the time interval between the crests of two waves, is associated with stronger wave energy and may result in the transfer of large amounts of sand (Bromirski et al. 2005). The direction of sand transport is dependent on the angle at which the swell approaches the beach (Peek & Young 2013), whereas the actual transportation of the sand is dependent on the longshore currents generated from wave energy. The flow and direction of longshore currents change depending on the waves energy and angle of approach. For a typical pocket beach, or small bay with rock outcropping on either end, longshore currents will excavate sand from one end of the beach and deposit it against rocks protruding in to water on the other end (Lizarraga et al. 2007; Peek & Young 2013). The direction in which sediments are transported is dependent on seasonal differences in swell direction. Weather anomalies that result in severe winter storms can affect wave energy and currents leading to drastic changes in beach morphology.

The El Niño-Southern Oscillation, or ENSO, refers to the irregular patterns of Pacific Ocean sea surface temperatures that characterize El Niño, La Niña, and ENSO-neutral years. El Niño occurs when sea surface temperatures off the west coast South America deviate from the long-term average or normal values, while an ENSO-neutral period is characterized by equatorial Pacific Ocean temperature that fall near the long-term average. An El Niño will increase winter storm activity during one year and will occur at irregular intervals every two to seven years thereafter (Bromirski & Flick 2005). During unusually stormy winters, beaches in Central California can experience a decrease in beach width of up to 150 meters. Having wide beaches in front of a cliff buffer the effects of erosion caused by wave energy (Barnard et al. 2012**)**. Beach width decreases as longshore currents excavate and transport sediments. Seventy six percent of coastal erosion in the past has likely occurred during El Niño events (Storlazzi & Griggs 2000). Northern California beaches are more exposed to winter wave energies than Southern California beaches that are sheltered by islands (O'Reilly et al. 2016). The winter storms formed during an El Niño have a great impact on beach morphology and coastal erosion in Northern California

While the morphology of a typical sandy beach system is well understood, less is known about the intertidal boulder fields that are a common feature of the coastline in Northern California. Boulders, defined as rocks more than 26 cm in diameter, can alter the flow pattern of water moving around them when submerged at high tide. The altered water motion may affect sediment transport, suggesting that basic patterns of sedimentation within an intertidal boulder field may be different from patterns on a sandy beach. Through studying the fluctuations of sedimentation within a boulder field, a better understanding of the morphology of these systems may be reached and generalized for other regions along the California coast. Sedimentation in an intertidal boulder field has implications for the organisms living with in it as well as processes of erosion for the sea cliffs surrounding. The objective of this study is to describe how sedimentation in an intertidal boulder field in Northern California changes seasonally, and during ENSO events. In this study, I test the hypotheses that sedimentation within a boulder field (1) changes over time, (2) will be different among seasons, and (3) will be different during an El

Niño event than during an ENSO-neutral event. These hypotheses will be tested using qualitative comparisons of sedimentation derived from monthly photographs of the boulder fields. Empirical measurements of sand depth will be used to validate the qualitative comparisons.

METHODS

Beach morphology study sites

Located within the Point Reyes National Seashore, The sites examined in this study are exposed to waves generated by local winds and distant storms in both hemispheres (Burrows et al. 2008). The intertidal zones of the study sites have large boulders that provide a consistent reference point for visual comparisons of sand amount over time. Kehoe Beach (38°9’56.08” N, 122°57’6.04” W) is located on the south side of a rocky headland and McClures Beach (38°11’2.70” N, 122°58’2.33” W) is located on the north side of a rocky headland (Fig. 1 & 2). This region of the California coastline is characterized by larger waves in the winter and smaller waves in summer (Fig. 3), with even larger waves occurring during El Niño events (Martin et al. 1993; Sallenger et al. 2002).

Fig. 1. Study site location in reference to San Francisco.

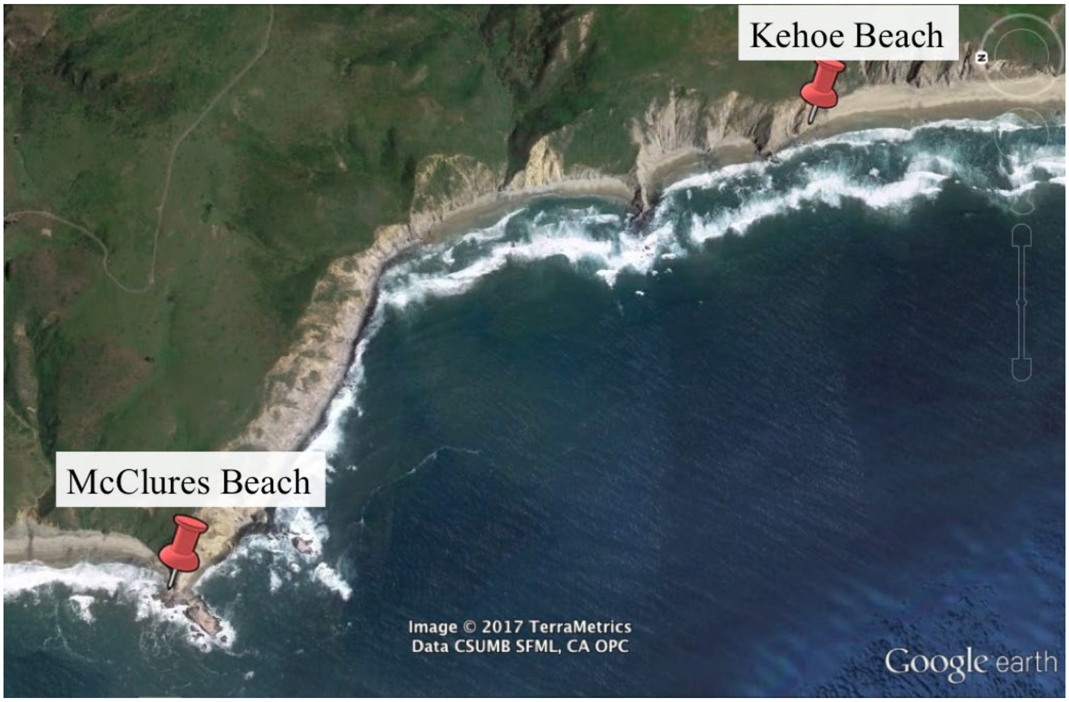

Fig. 2. Study Site locations on McClures Beach and Kehoe Beach.

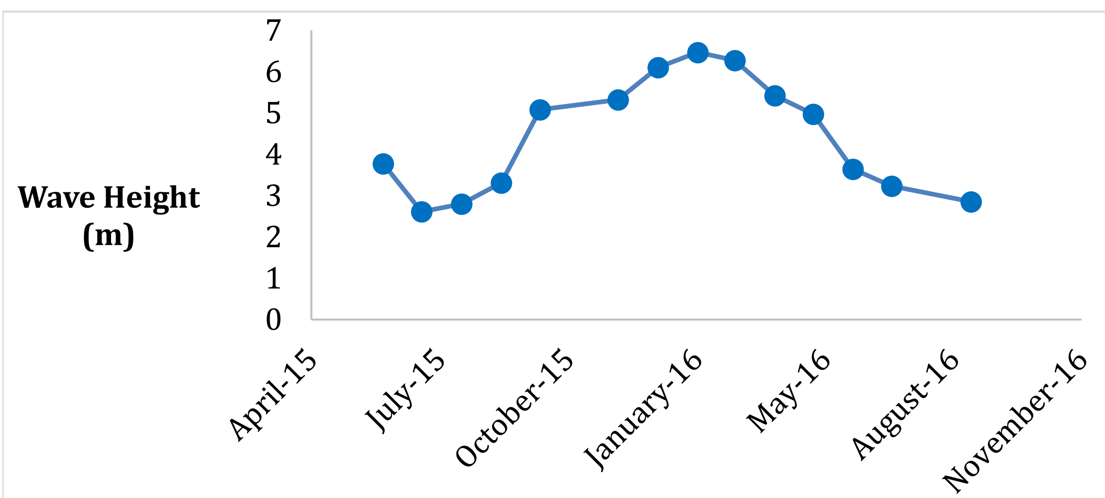

Fig.3. Seasonal change in maximum significant wave height measured from a NOAA buoy close to the study sites.

Beach morphology rank

Sediment amount was monitored with photographs taken at each of the sites from September 2014 to March 2017. Photographs were taken approximately once per month during spring low tides (tidal height < 0.5m above MLLW) from a similar vantage point at each of the sites. Photographs were ranked in order of relative sand amount using randomized pairwise comparisons. That is, photos were assigned random numbers and individually compared to every other photo. For example, 20 photographs would give rise to 400 comparisons (Table 1). In each comparison the photo that appeared to have more sand was assigned a score of 1 and the photograph with less sand was assigned a score of 0. A photograph's rank was the sum of its scores for all of its respective comparisons. A photo with the highest possible rank would have the largest amount of sand relative to all other photos for that site.

Table 1. Example of Randomized pairwise comparisons for 5 pictures. The columns consist of the scores that were given for that monthly photograph in comparison to all other photographs.

	3377	8765	9211	4701	3850
3377	NA	0	0	0	0
8765	1	NA	1	1	1
9211	1	0	NA	1	1
4701	1	0	0	NA	0
3850	1	0	0	1	NA

Sand depth

Sand depth was measured at each site along two transects (length = 30 m) that were placed parallel to the shoreline. One transect was located near the water (i.e. a low shore measurement), and the second transect was located approximately 2 m higher on the shore (i.e. a high shore measurement). For each measurement, an aluminum rod was pushed vertically into the sand until it reached solid rock, and the sand depth was recorded as the length of the rod covered by sand to the nearest 1 cm. Measurements were made at 2 m intervals along the transect. Sand depth was measured in a similar area each month.

Statistical analysis

All statistical analyses were done in base R (version 3.3.2, Vienna, Austria). I tested for a correlation between sand depth and rank using a linear regression. Differences in rank were compared among seasons at each site using a non-parametric Kruskal-Wallis rank sum test. Beach ranks were compared between El Niño and ENSO-neutral winters using a Wilcoxon rank sum test.

RESULTS

Ground truthing visual comparisons

The ranks of beach morphology were positively correlated with field measurements of sand depth (Fig. 4). Two years of monthly ranks for relative sand amounts reveals two large

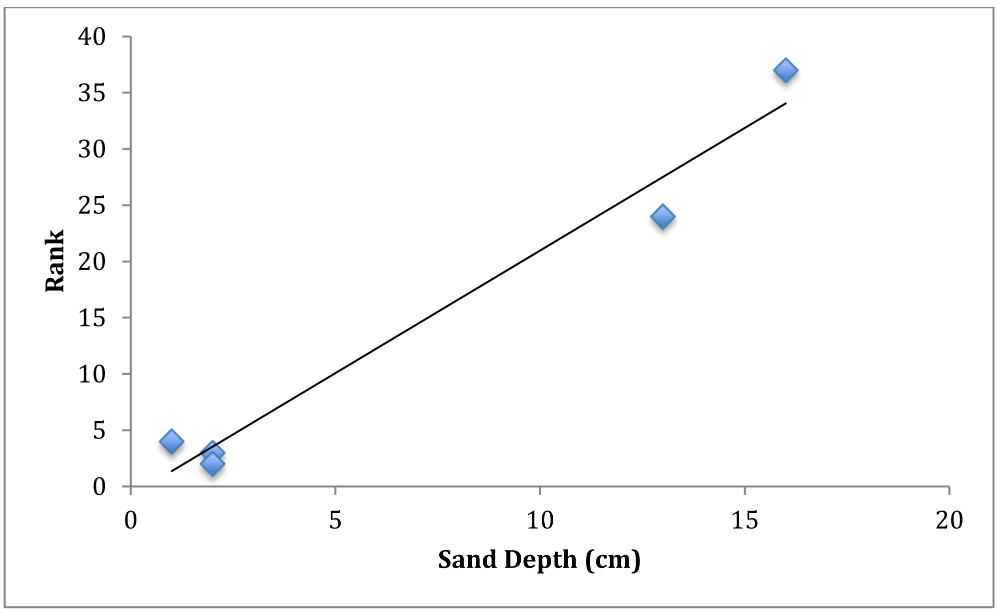

Fig. 4. The beach morphology rank and measured sand depth for Kehoe Beach (linear regression, y = 2x-1, P = 0.002, R^2 = 0.97.

oscillations with annual changes in beach morphology for each site. In 2015, ranks for McClures Beach fluctuated between a maximum of 22 and a minimum of 1, and in 2016 with a max of 18 and min of 3 (Fig. 5). Kehoe Beach had a maximum rank of 21 and a minimum rank of 0 in 2015, and then a maximum of 18 and a minimum of 0 in 2016 (Fig. 5).

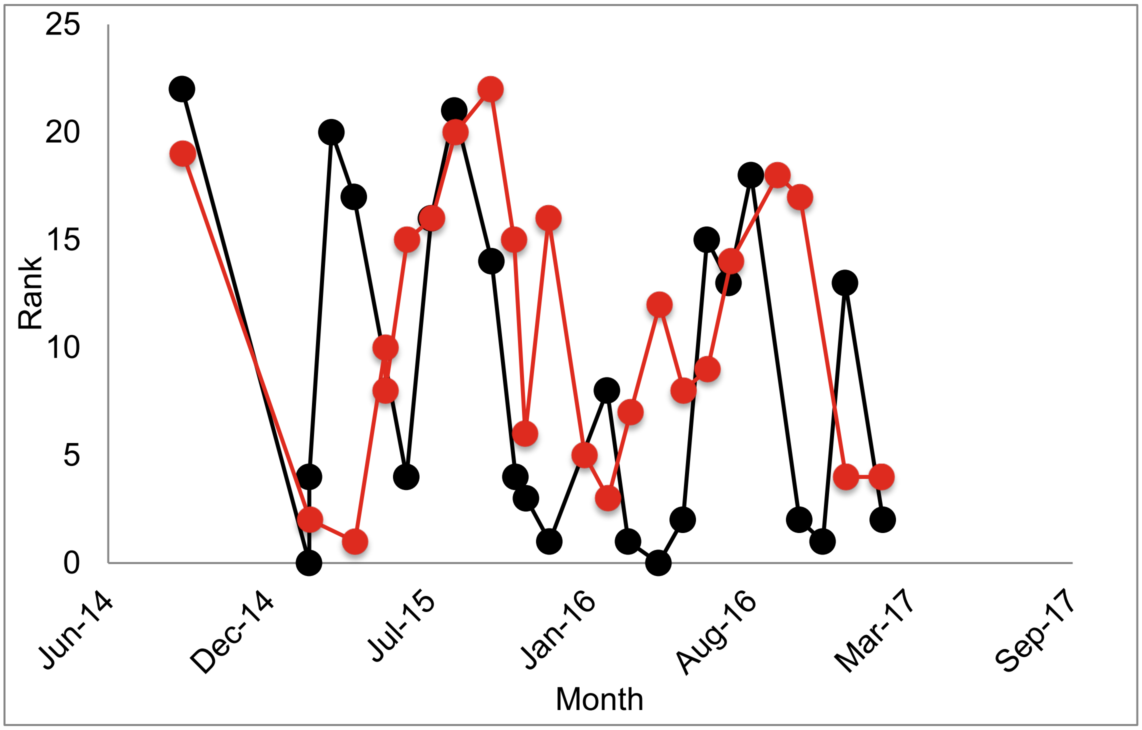

Fig. 5. Rank of beach morphology at McClures Beach (Red) and Kehoe Beach (Black) from September 2014 to January 2017.

Seasonal Beach Morphology

At Kehoe Beach the maximum rank of sand depth occurred in the fall (rank = 22) and the minimum rank occurred in the spring (rank = 0) (Table 2). There were no significant differences in beach morphology among seasons during the 2-year study period for Kehoe Beach (Kruskal-Wallis test, $X^2 = 4.78$, d.f. = 3, P = 0.19) (Fig. 6). At McClures Beach the maximum (rank = 22) and minimum (rank = 1) ranks of sand depth also occurred in fall and spring, respectively (Table 3). Unlike at Kehoe Beach, the beach morphology at McClures Beach was different between the fall and winter seasons (Kruskal-Wallis test with post hoc Dunn test, $X^2 = 11.02$, d.f. = 3, p = 0.01, n = 6) (Fig. 6). The lowest ranks occurred in the winter (median = 4). The median for each season increased from spring through fall and then decreased in the winter (Table 2).

Table 1. Median, minimum, and maximum ranks among seasons for Kehoe Beach. N= number of observations.

Season	N	Median	Minimum	Maximum
Spring	5	2	0	20
Summer	6	16	4	21
Fall	6	4	1	22
Winter	5	2	1	13

TABLE 2. Median, minimum, and maximum ranks among seasons for McClures Beach. N= number of observations.

Season	N	Median	Minimum	Maximum
Spring	5	8	1	12
Summer	5	15	9	20
Fall	6	18	6	22
Winter	6	4	2	16

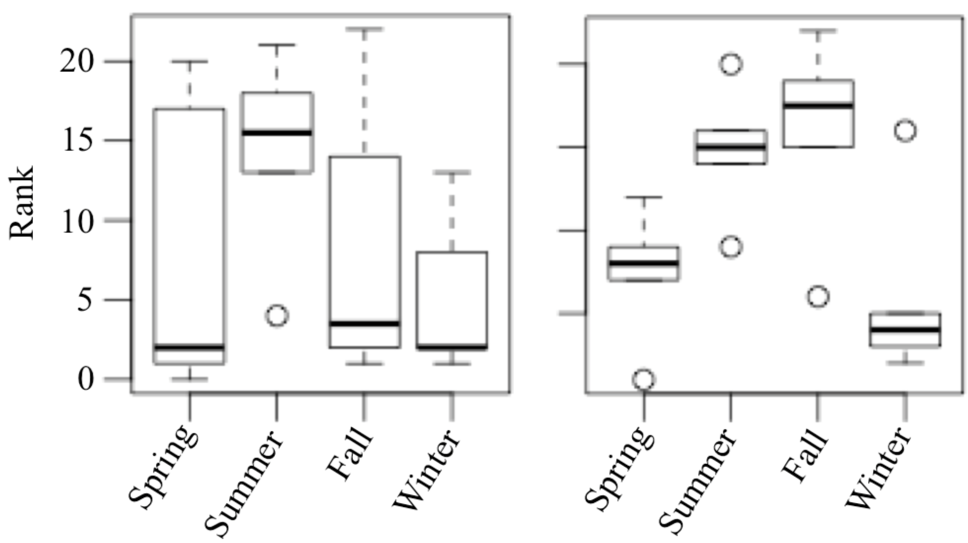

Fig. 6. Beach morphology during different seasons for Kehoe Beach (at left) and McClures Beach (at right).

Beach Morphology during ENSO events

Our study period encompassed an El Niño event (2015-2016 winter) and two ENSO-neutral years (2014-2015 winter and 2016-2017 winter). Beach morphology rankings were similar between sites during El Niño winters (Mann-Whitney U test, P = 0.80, n = 3) and also during ENSO-neutral winters. Therefore, ranks were pooled from the two sites to compare beach rank between El Niño and ENSO-neutral winters. The distributions of the ranks were not different between the two types of winters (Mann-Whitney U test, P = 0.52, n = 6) (Fig. 7), but El Niño winters had a greater median and maximum beach morphology in ranks than ENSO-neutral winters (Table 3).

Table 3. Comparing median ranks between El Niño and ENSO-neutral winter conditions with combined ranks among sites.
N= number of observations.

Winter Year	N	Median	Minimum	Maximum
2015-2016	5	5	1	16
2016-2017	6	3	2	13

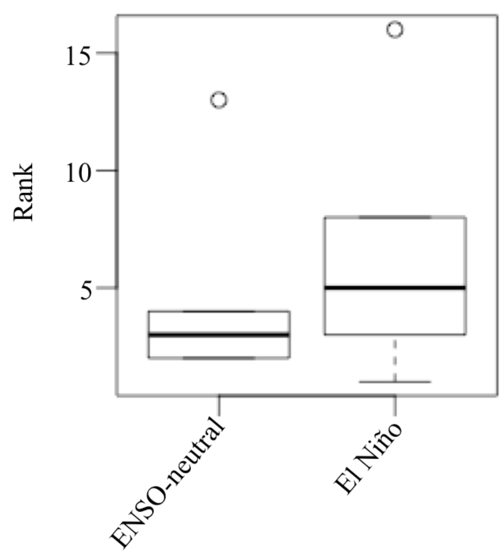

Fig. 7. Rank comparison between ENSO-neutral winter and El Niño winter.

DISCUSSION

Boulder field sedimentation (physical consequences)

Effects of seasonal changes in waves and currents

Beach morphology for McClures Beach followed the expected seasonal trend with differences in rank between seasons, while Kehoe Beach experienced more variation in sedimentation throughout a given year (Fig. 3). Many sandy beaches along the California coast undergo seasonal changes in beach morphology, resulting in more sand in the summer than in the winter (Storlazzi & Griggs 2000; Lizarraga et al. 2007). The boulder fields at McClures Beach exhibited similar patterns of sedimentation suggesting that we would observe a greater amount of sand during the summer and fall months in comparison to other times of the year. This would follow the seasonal swell pattern of the region with smaller waves occurring during the summer than in the winter (Bromirski et al. 2005). However, Kehoe Beach did not follow a pattern similar to the one described above. Kehoe Beach had much more variation in rank among each season. There were no differences in sedimentation between seasons with a much larger spread in rank for each season in comparison to McClures Beach. This was an unexpected result because both of the beaches are located geographically close to one another and were hypothesized to have similar fluctuations in sedimentation. If fluctuations of sedimentation did not follow a seasonal trend, then it is likely that the location of Kehoe Beach experiences processes of sand transport that differs from McClures Beach. This may be specific to the beaches' exposures to swell and their surrounding geological features.

Effects of coastal geography

The location of the two sites in reference to nearby rocky headlands and the direction in which the beaches face may lead to different swell exposures and could explain the variation in sedimentation at Kehoe Beach (Restrepo & Lopez 2008). Kehoe Beach is located on the south side of a headland and faces the southwest direction while McClures Beach faces more of a Northwest direction and is located on the north side of the headland. It is likely that being located on the south side of the headland gives this beach more exposure to southwest wind swells or perhaps larger southerly groundswells during the summer months that Mclures is more protected by as the headland may shelter this beach from this direction of wave action (Masselink & Pattiaratchi 2001). If this is true, Kehoe Beach may be exposed to a larger wave window than McClures, where it receives west wind swells and southwest groundswells in addition to the large winter north swells. Our study site at McClures Beach may be more protected from wave action from the west and southwest, while experiencing a majority of wave action from the north swells in the winter. The sheltering of wave action by the headland could explain why more sand was observed to accumulate during the summer and fall months at McClures Beach (Sallenger et al. 2002). While more variation at Kehoe Beach could be the result of exposure to multiple swell and wind directions.

Effects of extreme events

Sedimentation at the two field sites was similar between the El Niño and ENSO-neutral winters (Fig4). However, there were individual observations of deeper sand that were greater in El Niño than ENSO-neutral winters resulting in a higher median of rank. More sand may have been observed in both of the study sites due to the unusual angle of winter swells during an El Niño (Sallenger et al. 2002). More sedimentation with in the boulder fields during an ENSO event could suggest certain locations of a beach system are actually less susceptible to sea cliff erosion. A boulder field that is covered by sediments could act as a wide sandy beach, decreasing wave run-up that leads to sea cliff erosion (Prodger et al. 2000). This contrasts the study of Storlazzi et al. (2000) that found that the south ends of pocket beaches were more susceptible to erosion while our data would seem to suggest the opposite. In fact, the 2016-2017 winter following the El Niño led to much greater erosion around our study sites and for the whole coastline of California. It is possible that many sea cliffs experience more wave run-up during the El Niño winter, leading to the weakening of bluffs and susceptibility of slides (Emery & Kuhn 1982). Even though this may not be consistent with the findings of this study, I believe other locations of beach systems were more susceptible to erosion or sea cliff weakening like studies on the central California coast would support (Sallenger et al. 2002). It is likely that regions of sea cliffs that experienced wave run-up during the El Niño winter were more susceptible to erode during the heavy rains the following winter.

Implications for land management

Understanding local processes of erosion and monitoring seasonal fluctuations could assist with land and resource management decisions. Our results support that seasonal fluctuation of sedimentation in a boulder field may be more variable for some locations than others even if they are near each other. In this case it would be beneficial to encourage beach going at Mclures Beach during the summer and fall when walking in this area would be easiest as there are very few boulders or rocks to navigate. The seasonal fluctuation of sand present in the boulder field may be more predictable for the south end of McClures Beach as it is sheltered from a headland. Accessing McClures Beach in the winter could be treacherous as water can reach the base of the sea cliff on the high tide and may result in stranded beachgoers. It may be preferred to protect the sensitive intertidal organisms that inhabit this region of McClures Beach during the winter from foot traffic. Knowing that most of these boulders are covered by sand in the summer and fall, perhaps tide pooling can be encouraged during the winter low tides when more intertidal organism are present. As for Kehoe Beach where we found sedimentation to be more variable, beach goers should be informed to use their discretion when accessing this location year round as its orientation may make it more exposed to wind and wave action throughout the year. It is possible that this exposure also makes Kehoe Beach more susceptible to erosion. It may be of interest for patches of coastline with similar orientation and wave and wind exposure to go undeveloped, as these sea cliffs may be vulnerable to slides.

The expected increase in frequencies of El Niño events and large storms may actually mitigate processes of erosion for beach system with similar orientation to our two study sites (Sallenger et al. 2002). Finding that individual observations of sand rank were greater in El Niño than ENSO-neutral winters suggests that there was more sand deposition in each of our study sites during the El Niño. With sand accumulation in these areas acting as a buffer to sea cliff erosion and wave run up, one may consider these sea cliffs to be less susceptible to erosion. This would influence the decision to keep the current land management system of coastal areas with similar orientation to our study sites, as these bluffs may be more stable than other regions.

Changes in the amount of sand with in a boulder field will also have biological consequences on intertidal organisms.

Biological effects

Sedimentation on rocky intertidal shorelines can negatively affect organisms in that habitat, especially sessile organisms on the rocky substrata. Plants, seaweeds, and invertebrates with poor attachment to the rocky surface can be removed by sand scouring (Antonio 1986). Additionally, sand burial can decrease the availability of light, oxygen, and suitable substrata to intertidal flora such as algae and kelp (Littler et al. 1983). As a result, rocky intertidal zones that have experienced sedimentation can have decreased biodiversity (Chapman 1946, Stephenson 1972, Phinney 1977). However, some species of anemones, algaes, and crustaceans are able to thrive in sand swept intertidal zones because of their adaptations to sediment disturbcances (Doty 1947, Mathieson 1965, Markham & Newroth 1972).

Sand stressed habitats primarily serve as important refuges for stress tolerant strategists and opportunistic strategists (Littler et al. 1983). Species' abundances and distributions are influenced by species-specific adaptation to the intensity of sediment disturbance (Bretz 1995). Areas in the central California coast with heavy seasonal sediment deposition (covered by more than 10cm of sand for longer than 3 weeks) contained a mixture of fleshy brown and red algae. For example, *Rhodomela larix* is a red alga that can survive lengthy anoxic burial and severe sand scour (Antonio 1986). Herbivores and epiphytes that feed on sand tolerant algae may be negatively affected by sand burial and scouring. For *R. larix*, sandy sites may serve as refuges from competitors, herbivores, and epiphytes. The anemone *Polysiphonia pacifica* dominated areas classified to have low sediment cover (Bretz 1995). The distribution of the mole crab, a typical inhabitant of sandy beaches, is strongly influenced by grain size and morphology of the beach deposit (Bowman & Dolan 1985). The mole crab, *Emerita*, will aggregate and burrow up to 5cm depth in upper beach areas, and their numbers and burrowing depth will increase near the lower beach swash zone. Emerita would be found among the finer sediments deposited in a boulder field where sand depth was at least 5cm (Michael & Dolan 1985). *Ulva* spp. is a green alga that has been found to dominate sites where sand burial is intermediate in severity; exposure of boulders lasted for 3 months.

Temporal fluctuations in sedimentation could result in higher biodiversity within an intertidal boulder field. With sedimentation fluctuating with more of a seasonal trend at McClures Beach in comparison to Kehoe Beach, sand burial and scouring could serve as an intermediate disturbance that could result in higher species richness at this location. While more frequent burying and uncovering of the intertidal boulder field, like that at Kehoe, would be unfavorable for organisms to inhabit and may result in a higher temporal disturbance level than McClures Beach (Fig. 3) (Souza 1979a). With more variation in the amount of sand present with in the boulder field during a year, Kehoe Beach may have a higher disturbance level than McClures Beach (Fig. 3). A more seasonal trend in sedimentation like that found at McClures Beach could represent an intermediate level of disturbance leading to greater species richness in this boulder field (Fig 3). Boulders and rocky patches provide additional living spaces for macrofauna and increase local biodiversity in habitats that would otherwise be inundated by soft sediments (Grzelak & Kukliinski 2010). The boulder fields with intermediate levels of sedimentation may be beneficial to many types of intertidal organisms. The inundation of boulder fields by sand could lead to a different, and possibly less diverse, assemblages of organisms.

Limitations

The unanticipated result of Kehoe Beach having large month-to-month fluctuations of sedimentation with little seasonal variation may have been due to the one observation of beach morphology that occurred each month. With more than one photograph being taking per month, we would have better resolution of how quickly the month-to-month fluctuation was occurring. One observation per month may not be representative of the amount of sand that was deposited in the boulder field during that month. Limited observations of beach morphology to compare seasonal difference for each site may have been a confounder for detecting differences. With a limit of either 2 or 3 observations of beach morphology during the winter categorized as El Niño, we may have not been able to detect differences in sedimentation for each site when comparing El Niño winters to ENSO neutral winters. The measurements of sand depth and their correlation to rank were not representative of intermediate ranks. We only had sand depth measurements corresponding to low ranks from 0 to 5, and higher ranks of 20 to 40. We were not able to see how our method held up for intermediate ranks from 5 to 20. While rank had a strong positive correlation with sand depth measurements, visual comparisons may not have been able to detect slight differences in sand amounts between photos.

Future Directions

Analysis of buoy data and sea surface currents may have been beneficial for understanding the wave energy and swell direction that led to large fluctuations in sedimentation. I think that it would be interesting for this method to be applied to different beach systems that have higher temporal resolution (comparison of photographs taken during the same month) during an El Niño winter. It would be interesting if another study in the same location or in another could find observations of rank that were higher in the El Niño winter in comparison to other winters. It would also be interesting to take a closer look at the type of sediments that were being deposited in the boulder field during an El Niño winter. I would hypothesize that the sediments that were collecting in the boulder during an El Niño may have a different composition or distribution in grain size than sediments during an ENSO-neutral winter. It would have been useful to know the grain sizes of the sediments I was taking depth measurements in. Measuring the range of grain sizes present would reflect the energy levels in the depositional environment and how they change over time (Lewis & McConchie 1994). This would be useful for knowing how flow velocities generated from wave energy varied in each site over a given year.

Evaluation of Method and implications for other systems

My method of ranking beach morphology for the two-year time period detected monthly changes in beach morphology. I found that field measurements of sand depth with in a range from 0 to 16 cm had a strong positive correlation to rank (Fig. 1). This shows that the human eye is capable of detecting minor changes in sand amount when comparing two pictures. The method can be an effective way to study minor changes in beach morphology over time in a remote location. The public regularly photographs many culturally important places and those pictures are uploaded to online databases or social media (e.g. Instagram, Facebook). Further application of this method could show how a time series of pictures could reveal topographical changes such as erosion or development, while helping communicate to the general public that our shorelines are actively changing from processes such as increased storm activity, wave heights, and sea level rise.

ACKNOWLEDGEMENTS

I would like to give a special thanks to my mentor, Nicholas Burnett, who provided countless hours in assisting me with writing this paper, driving to Point Reyes, and making this thesis possible. Nicholas made sure that my research improved my scientific thinking and writing abilities. Dylan Chapple played a key role in helping organize my scattered thoughts to tell a coherent story which has hopefully been formed above. Nicholas and Dylan helped transform this paper from a very rough piece of amateur scientific thinking to a thoroughly reviewed piece of literature. Peer reviewers Vincent Spadone and Saba Saberi were also very helpful in their constructive criticisms of my writing. The whole ESPM 175 class of 2017 was a very inclusive and supportive group. Patina Mendez and Kurt Spreyer did a wonderful job of organizing a course that gave me a foundation from which I will continue to build off for whatever future career I pursue. Lastly, I would like to thank all of my family members who have made this opportunity to study at Berkeley's College of Natural Resources possible. I sincerely thank all those individuals mentioned above!

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