Exploring linkages between coastal progradation rates and the El Niño Southern Oscillation, Southwest Washington, USA

L. J. Moore,[1,2] G. M. Kaminsky,[3] and H. M. Jol[4]

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[1] Climate oscillations such as the El Niño-Southern Oscillation (ENSO) affect storm tracks, wave climate, precipitation and sea level in the U.S. Pacific Northwest. The impacts of these changes on coastal behavior have not been investigated in detail beyond the study of recent El Niño events, largely because existing historical records of coastal behavior are not of sufficient resolution to study annual responses to climatic forcing. We compare a newly developed annual record of coastal progradation for a location on the Washington coast, generated using high-resolution subsurface ground penetrating radar (GPR), with ENSO indices. This analysis reveals higher rates of seaward coastal growth following the warm, El Niño, ENSO phase and lower rates of coastal growth following the cold, La Niña, ENSO phase. The observed relationship between ENSO and progradation, although weak, is hypothesized to result from differences in sediment transport patterns and beach recovery rates following El Niño and La Niña events. *INDEX TERMS:* 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 3020 Littoral processes; 4522 Oceanography: Physical: El Niño; 4556 Sea level variations; 1620 Global Change: Climate dynamics (3309). **Citation:** Moore, L. J., G. M. Kaminsky, and H. M. Jol, Exploring linkages between coastal progradation rates and the El Niño Southern Oscillation, Southwest Washington, USA, *Geophys. Res. Lett.*, *30*(9), 1448, doi:10.1029/2002GL016147, 2003.

1. Introduction

[2] The Columbia River littoral cell (CRLC), extending from Tillamook Head, OR to Point Grenville, WA on the Oregon and Washington coastline, has been accretional, prograding seaward and aggrading (vertical growth), for at least the last 1.5 Ka [*Peterson et al.*, 1999] (Figure 1). The Columbia River has been a major supplier of sand to this littoral system and is largely responsible for the wide accreting beaches to the north and south of the river [*Ballard*, 1964]. Within the CRLC, sediment transport along the shelf is largely to the north [*Kaminsky et al.*, 2000] while littoral sand transport within the subcells reverses seasonally. Beginning in the mid 20th century, the emplacement of dams throughout the Columbia River drainage basin began to reduce sediment supply to the CRLC. The inception of flow regulation in 1969 [*Sherwood et al.*, 1990] further reduced Columbia River sediment supply to this region. More importantly, the emplacement of jetties in the late 19th and early 20th century at both Grays Harbor and the Columbia River resulted in onshore transport of sand from ebb-tidal deltas which generated decadal, regional scale coastal progradation along both the northern and southern adjacent coasts [*Kaminsky et al.*, 1999]. For decades (including the time period of study) this signal overwhelmed the influence of Columbia River sediment supply.

[3] The current investigation was undertaken in Ocean Shores, WA. Ocean Shores is located 60 km north of the Columbia River mouth in the northern-most subcell of the CRLC (Figure 1) and for this reason it is less responsive to changes in Columbia River sediment supply than the southern subcells. The time period of study, 1886 to 1950, was selected for two reasons: 1) the high progradation rates occurring throughout this time period, primarily as a result of the Grays Harbor north jetty emplacement between 1908 and 1916 [*Buijsman et al.*, 2003], are rapid enough to allow preservation of an annual signal that can be quantified and placed in time with some confidence (L. J. Moore et al., Annual layers revealed in the subsurface of a prograding coastal barrier, submitted to *Journal of Sedimentary Research*, 2002, hereinafter referred to as Moore et al., submitted manuscript, 2002), and 2) annual records of ENSO variability are available for this time period.

[4] Here we apply the classic "tree-ring approach" to a coastal setting in order to better understand the response of a progradational coastal system to variable climate forcing over a historical time period. To meet this objective, we first use geophysical tools to develop a record of annual coastal progradation, or "growth," and then compare this record with ENSO indices. Here we assume that the effects (or non-effects- prior to 1910) of jetty construction occur on a longer-than-annual temporal scale such that annual variations in progradation, superimposed on trends due to the presence of the jetty, may be related to annual climate oscillations. Though we only address the potential affect of climate variability in this analysis, antecedent effects (e.g. multiple consecutive storm years) or storm chronology (e.g. two moderate storms back to back vs. one intense storm) may also be important in producing variations in annual coastal progradation.

2. Ocean Shores Aggradation Rates

[5] *Meyers et al.* [1996], *Jol et al.* [1998] and *Smith et al.* [1999] documented that subsurface records of progradation and coastal behavior through time are preserved in the

[1]College of Marine Science, University of South Florida and U.S. Geological Survey, Center for Coastal and Watershed Studies, USA.
[2]Now at Oberlin College, Geology Department, 52 West Lorain Street, Oberlin, Ohio, USA.
[3]Coastal Monitoring & Analysis Program, Washington Department of Ecology, USA.
[4]Department of Geography and Anthropology, University of Wisconsin, Eau Claire, Eau Claire, Wisconsin, USA.

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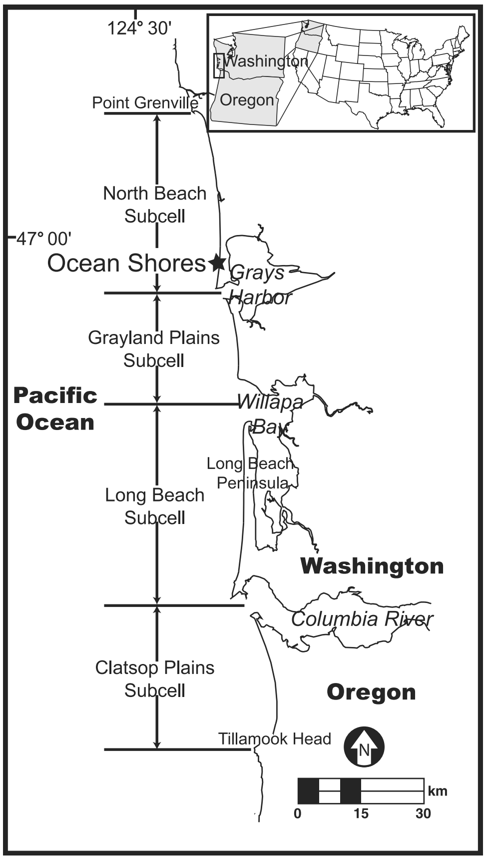

Figure 1. The CLRC extends from Tillamook Head, OR to Pt. Grenville, WA. Ocean Shores is located in the North Beach Subcell.

sandy subsurface of the southwest Washington coastline as highly reflective, seaward dipping layers that can be visualized using GPR. Moore et al. (submitted manuscript, 2002) demonstrated, for a location in Ocean Shores, WA (5 km north of Grays Harbor), that reflections on a 200 MHz GPR transect depict subsurface layers of high temporal resolution (Figure 2).

[6] Field observations indicate that the subsurface layers in Ocean Shores result from vertical variations in electromagnetic properties of the sediment generated by magnetite-rich heavy mineral lags. These lags, left annually on the active beachface by winter storms, are separated by thick intervening summer progradational beach deposits. Moore et al. (submitted manuscript, 2002) used known historical shoreline positions for 1886, 1927 and 1951 to place the subsurface reflections in time and found one subsurface reflection per year between 1886 and 1951. After a modeling exercise to demonstrate that each reflection represents one subsurface layer, Moore et al. (submitted manuscript, 2002) conclude that summer progradation was sufficiently rapid to prevent winter storms from completely eroding into heavy mineral lag layers left during previous winters. Finally, Moore et al. (submitted manuscript, 2002) measured the vertical spacing between subsurface layers to construct an annual record of aggradation (Figure 3), as a proxy for progradation (horizontal growth), in Ocean Shores.

[7] The resulting time series represents seaward growth occurring between winter lag deposits, and is therefore primarily a measure of summer progradation. The time series, which terminates in 1950, indicates vertical beach growth rates of 23–48 cm/yr with an average rate of 33 cm/yr. Assuming an average beach slope of 1.4° (based on local observations), this represents 9–19 m of annual progradation with an average rate of 13 m/yr between 1886 and 1950. Vertical measurements are repeatable to within 2.5 cm (= 1.0 m horizontal) and timing is estimated to be good to ±1 year (Moore et al., submitted manuscript, 2002).

3. Coastal Oceanographic Effects of ENSO

[8] Although the El Niño Southern Oscillation (ENSO) is largely a tropical phenomenon, it has a significant impact on the U.S. Pacific Northwest (PNW) coast, affecting winter storm tracks [*Mote et al.*, 1999], wave climate [*Komar et al.*, 2000; J. C. Allan and P. D. Komar, Spatial and temporal variations in the wave climate of the North Pacific, unpublished report, 2000, hereinafter referred to as Allan and Komar, unpublished report, 2000], sea level [*Huyer et al.*, 1983; *Komar et al.*, 2000] and precipitation [*Mote et al.*, 1999]. During the warm ENSO phase (El Niño) the Aleutian Low pressure center located in the North Pacific Ocean

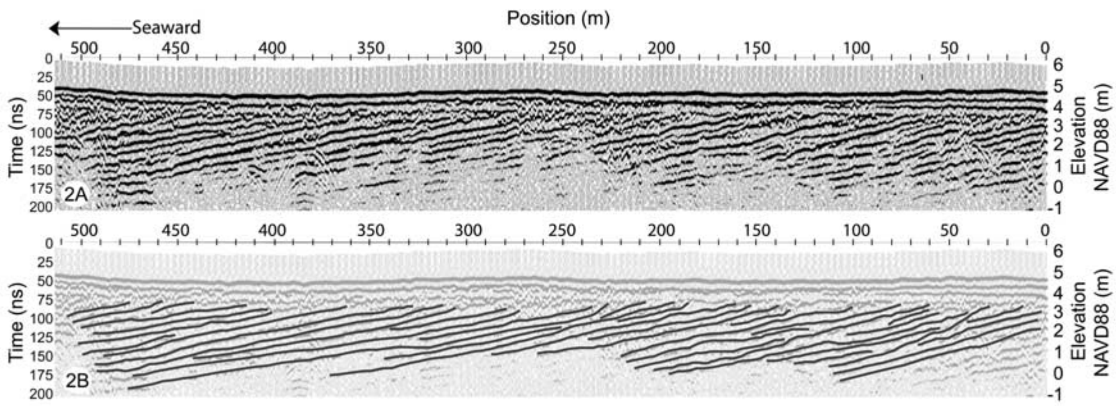

Figure 2. Seaward dipping, gently sloping (10x vertical exaggeration) subsurface layers found in Ocean Shores, WA. The first 500 m of the 980 m GPR transect are shown in A. Interpretations appear as dark lines in B.

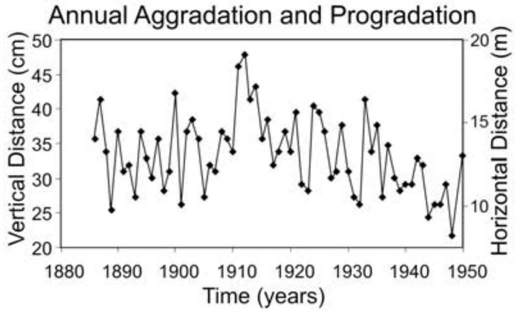

Figure 3. Annual aggradation and progradation at Ocean Shores, WA between 1886 and 1950 derived from subsurface 200 MHz GPR records. Average annual aggradation rate is 33 cm.

is strong. Under these conditions, the Pacific winter storm track tends to split around the PNW bringing storms to Alaska and California, and waves to the PNW coast from the southwest [*Seymour*, 1998; *Kaminsky et al.*, 1998; *Komar et al.*, 2000; *Mote et al.*, 1999]. In addition, sea level tends to be elevated 25–35 cm above normal during El Niño winters [*Huyer et al.*, 1983; *Kaminsky et al.*, 1998; *Komar et al.*, 2000].

[9] In contrast to El Niño conditions, during the cold ENSO phase (La Niña), the Aleutian Low is weak, allowing storms to follow their usual course more directly over the PNW. Thus, during La Niña, the PNW coast experiences larger waves directly from the west and a corresponding increase in wave energy [*Komar et al.*, 2000]. *Komar et al.* [2000] studied the 1997–98 El Niño and 1998–1999 La Niña events. Although El Niño events bring higher sea levels (and thus higher than predicted tides) to the PNW [*Komar et al.*, 2000] the analyses of *Komar et al.* [2000] suggest that due to increased wave energy, total sea level (measured tides + storm surge + wave runup) is higher, and

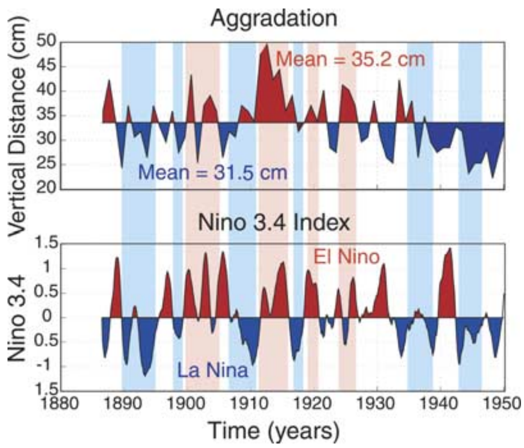

Figure 4. Aggradation in Ocean Shores WA and the Niño 3.4 Index [http://iridl.ldeo.columbia.edu/SOURCES/.KAPLAN/.Indices]. Aggradation values above and below the mean are shown in red and blue, respectively. In the bottom panel El Niño and La Niña values are shown in red and blue, respectively. Light red (blue) bands highlight corresponding El Niño (La Niña) events and high (low) aggradation values.

Table 1. Summary Statistics, Comparison with JMA SSTA Index

	La Niña	El Niño	Neutral
Number of events	16	12	36
Minimum aggradation rate (cm/yr)	21.6	27.3	26.3
Maximum aggradation rate (cm/yr)	38.5	46.1	51.7
Mean aggradation rate (cm/yr)	31.5	35.2	34.1
Standard deviation	5.0	5.5	6.3

thus winter erosion should be greater, along the PNW coast during La Niña events. However, *Komar et al.* [2000] found that although La Niña caused widespread coastal erosion, the southerly track of El Niño storms generated severe localized winter erosion, typically at the southern end of littoral cells. In addition to differences in wave climate, storm tracks and sea level, precipitation in the PNW tends to be greater during La Niña years than during El Niño years [*Mote et al.*, 1999]. Although the winter effects of El Niño have been studied quite extensively (e.g. *Kaminsky et al.*, 1998; *Komar*, 1998; *Komar et al.*, 2000; P. Ruggiero, personal communication), the recovery of PNW coastal systems following an independent El Niño or La Niña event has yet to be documented.

4. Comparison With ENSO Indices

[10] Comparison of the annual aggradation time series, with the Niño 3.4 Index [http://iridl.ldeo.columbia.edu/SOURCES/.KAPLAN/.Indices] reveals that La Niña tends to be associated with lower aggradation rates while El Niño tends to be associated with higher aggradation rates (Figure 4). Analyses of the two time series do not yield a strong statistical correlation. However, since the timing of any one aggradation rate is ±1 year, the lack of a statistical correlation is expected and does not discount the possibility that there is a linkage between ENSO and fluctuations in annual coastal aggradation.

[11] Comparison of annual aggradation with the Japan Meterological Society Sea Surface Temperature Anomaly (JMASSTA) Index [http://www.coaps.fsu.edu/~legler/jma_index.html], which classifies each year (1868–present) as El Niño, Neutral or La Niña, suggests a relationship similar to that observed with the Niño 3.4 Index. The JMA annual classification is based on average monthly index values and selects known ENSO events well. The mean aggradation rate for all El Niño years during the time period of study is 35.2 cm/yr while the mean aggradation rate for all La Niña years is 31.5 cm/yr. The mean for all neutral years is 32.9 cm/yr. The difference between mean rates for El Niño years and La Niña years is 3.8 cm/yr representing a mean difference in progradation rate of 1.6 m/yr. Under a t-test, the difference between these means is marginally statistically significant at 90% with a confidence interval of 0.2–7.0. See Table 1 for a summary of statistics by ENSO phase.

5. Discussion

[12] As discussed above, recent studies document that ENSO alters sediment supply rates and erosional (or progradational) processes in the U.S. PNW by generating changes in winter precipitation, total sea levels and wave climate. For example, an increase in winter precipitation during La Niña leads to increased snow pack and thus

greater water discharge from the Columbia River and increased sediment supply to the coast. Increased sediment supply to a progradational coastal system generally leads to increased rates of coastal growth. However, because Ocean Shores is located approximately 60 km north of the Columbia River mouth, an increase in sediment supply over a 1–2-year period is unlikely to affect coastal growth rates at this site. This suggests that the observed effects of La Niña and El Niño in Ocean Shores may be due to other factors such as differences in wave climate, i.e. storm wave direction and storm wave energy, and/or differences in total sea levels.

[13] Based on the recent observations of ENSO effects on coastal processes, we hypothesize that differences in sediment redistribution during La Niña events compared with El Niño events, resulting from changes in storm wave energy and direction, are responsible for the different rates of recovery (i.e. different rates of summer progradation) observed following La Niña and El Niño events in the historical record. With larger waves and greater widespread erosion expected during La Niña than during El Niño [*Komar et al.*, 2000], there is likely increased transport of sand farther offshore during La Niña winters leading to less rapid recovery from winter erosion and, as a consequence, less summer progradation between winter lag deposits. In contrast, much of the sand eroded from the southern end of littoral cells during an El Niño winter is redistributed alongshore to the north, thus remaining readily available for rapid redistribution after storm conditions subside.

[14] The effects of differences in sediment transport caused by changes in storm wave energy and direction may be enhanced by differences in total sea levels during El Niño versus La Niña storms. Total sea levels as addressed by *Komar et al.* [2000] are complex and depend on a number of factors including storm strength. Since La Niña storms are expected to be generally more severe than El Niño storms, *Komar et al.* [2000] generally suggest that except for a "worst case" El Niño when a major storm occurs, total sea level will be higher during La Niña storms. Although more research is necessary, the relationship between higher total sea levels during La Niña storms and slower rates of summer progradation may be explained by greater offshore sand transport during intense La Niña events requiring a longer timescale (i.e. greater than a single summer) for waves to move the sand back onshore.

[15] The statistical relationship between coastal progradation and ENSO at Ocean Shores, although weak, is of interest because it suggests that changes in climatic forcing may elicit different coastal responses even over short time scales. The observed relationships also suggest that the effects of El Niño and La Niña events may extend beyond winter erosion to affect how rapidly the coastal system recovers from fluctuations in climatic forcing. Despite the value of considering hypotheses to explain our observations, it is important to note that the average difference in aggradation following El Niño versus La Niña is only 3.7 cm. This is equal to slightly more than 10% of the mean aggradation rate of 33 cm/yr, indicating that the ENSO signal at Ocean Shores is small. Perhaps this suggests that although ENSO may have some effect on progradation, the ENSO effect is not all that important. Alternatively, the Ocean Shores site may lack sensitivity to ENSO forcing because of its alongshore position within the littoral subcell. Continuing study of the relationship between subsurface records of coastal progradation and ENSO may provide clues regarding differing alongshore response and may strengthen the statistical relationship between progradation and climatic forcing. In addition, observations of the relative importance of cross-shore and alongshore sediment transport during La Niña versus El Niño events, as well as observations of beach recovery, are needed to support or contradict the hypotheses presented here.

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L. J. Moore, Oberlin College, Geology Department, 52 West Lorain Street, Oberlin, OH 44074, USA. (laura.moore@oberlin.edu)

G. M. Kaminsky, Coastal Monitoring & Analysis Program, Washington Department of Ecology, USA.

H. M. Jol, Department of Geography and Anthropology, University of Wisconsin, Eau Claire, Eau Claire, Wisconsin, USA.