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The impact of the 2009–10 El Niño Modoki on U.S. West Coast beaches

Patrick L. Barnard,[1] Jonathan Allan,[2] Jeff E. Hansen,[1,3] George M. Kaminsky,[4]
Peter Ruggiero,[5] and André Doria[6]

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[1] High-resolution beach morphology data collected along much of the U.S. West Coast are synthesized to evaluate the coastal impacts of the 2009–10 El Niño. Coastal change observations were collected as part of five beach monitoring programs that span between 5 and 13 years in duration. In California, regional wave and water level data show that the environmental forcing during the 2009–10 winter was similar to the last significant El Niño of 1997–98, producing the largest seasonal shoreline retreat and/or most landward shoreline position since monitoring began. In contrast, the 2009–10 El Niño did not produce anomalously high mean winter-wave energy in the Pacific Northwest (Oregon and Washington), although the highest 5% of the winter wave-energy measurements were comparable to 1997–98 and two significant non-El Niño winters. The increase in extreme waves in the 2009–10 winter was coupled with elevated water levels and a more southerly wave approach than the long-term mean, resulting in greater shoreline retreat than during 1997–98, including anomalously high shoreline retreat immediately north of jetties, tidal inlets, and rocky headlands. The morphodynamic response observed throughout the U.S. West Coast during the 2009–10 El Niño is principally linked to the El Niño Modoki phenomena, where the warm sea surface temperature (SST) anomaly is focused in the central equatorial Pacific (as opposed to the eastern Pacific during a classic El Niño), featuring a more temporally persistent SST anomaly that results in longer periods of elevated wave energy but lower coastal water levels. **Citation:** Barnard, P. L., J. Allan, J. E. Hansen, G. M. Kaminsky, P. Ruggiero, and A. Doria (2011), The impact of the 2009–10 El Niño Modoki on U.S. West Coast beaches, *Geophys. Res. Lett.*, *38*, L13604, doi:10.1029/2011GL047707.

1. Introduction

[2] Coastal communities worldwide face increasing risk of coastal erosion and inundation due to climate change, including sea level rise (SLR) and potentially increased storminess. Recent studies that focus on ice sheet dynamics and semi-empirical approaches relating global temperature to SLR have estimated that the rise in global sea level by 2100 may range from 0.75 to 2 m [e.g., *Pfeffer et al.*, 2008; *Vermeer and Rahmstorf*, 2009]. Along the U.S. West Coast, the impacts of SLR will be periodically enhanced due to the effects of short-term climate fluctuations such as the El Niño Southern Oscillation (El Niño), which can produce regional mean monthly sea level anomalies up to 30–40 cm due to the combination of increased ocean temperatures (steric effect), changes in Ekman transport of surface waters, and propagation of coastally trapped Kelvin waves [e.g., *Enfield and Allen*, 1980; *Huyer and Smith*, 1985; *Ryan and Noble*, 2002; *Bromirski et al.*, 2003]. These short-term increases in sea level dwarf those caused by gradual global SLR projected for the next several decades. In addition, coastal hazards are significantly related to wave climatology and several studies demonstrate increasing storm intensity, frequency, and wave heights in recent decades along the U.S. West Coast [e.g., *Graham and Diaz*, 2001; *Allan and Komar*, 2006; *Ruggiero et al.*, 2010a]. If these trends continue, the combination of large waves and higher water levels, particularly when enhanced by El Niños, can be expected to be more frequent in the future, resulting in greater risk of coastal erosion, flooding, and cliff failures.

[3] El Niño and its opposite phase, La Niña, represent extremes in climate variability originating in the tropical Indo-Pacific due to ocean-atmosphere interactions that have global effects on climate. Since the early 1950s, there have been 11 recognized El Niños with the 1982–83 and 1997–98 events being the strongest on record [*Larkin and Harrison*, 2005; *Lee and McPhaden*, 2010]. Along the U.S. West Coast, El Niños influence both ocean water levels and the predominant storm tracks and hence the regional wave climate in the North Pacific [e.g., *Graham and Diaz*, 2001; *Allan and Komar*, 2002]. During a major El Niño, the predominant winter extratropical storm tracks that are typically centered over the Pacific Northwest (PNW) coast of Oregon and Washington are shifted south, resulting in increased wave energy for the California coast [*Allan and Komar*, 2006]. Additionally, the more southerly storm tracks cause waves to reach the coast from a more southerly angle relative to the shore, which can lead to a net littoral sediment transport reversal or enhancement. These wave direction anomalies result in alongshore gradients in sediment transport that produce localized "hotspot erosion" at the southern ends of headland-bounded stretches of shore (littoral cells), and the accumulation of eroded sand offshore into deeper water and to the northern ends of the littoral cells [e.g., *Kaminsky et al.*, 1998; *Sallenger et al.*, 2002]. These

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[1] Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, California, USA.

[2] Coastal Field Office, Oregon Department of Geology and Mineral Industries, Newport, Oregon, USA.

[3] Department of Earth and Planetary Sciences, University of California, Santa Cruz, California, USA.

[4] Coastal Monitoring and Analysis Program, Washington State Department of Ecology, Olympia, Washington, USA.

[5] Department of Geosciences, Oregon State University, Corvallis, Oregon, USA.

[6] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

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El Niño related trends of littoral transport reversals and significant offshore sand transport have also been reported in Australia [e.g., *Short and Trembanis*, 2004].

[4] Classic El Niños (e.g., the major 1982–83 and 1997–98 events) are characterized by a maximum warm SST anomaly occurring in the eastern-Pacific (EP-El Niño) and are typically associated with anomalous atmospheric circulation patterns known as the Southern Oscillation. A second type of El Niño has also recently been documented that has dominated ocean-atmospheric conditions during the past two decades (e.g., 1990–94 and 2002–10), where the maximum warm SST anomaly occurs in the central equatorial Pacific with cold centers on both sides (CP-El Niño or El Niño Modoki (pseudo-El Niño)) [*Ashok et al.*, 2007]. This paper reports on the broad coastal impact of the 2009–10 El Niño Modoki within 9 U.S. West Coast littoral cells in high spatial and temporal resolution. The observed changes during the 2009–10 El Niño Modoki are considered in context with past coastal behavior learned from inter-annual measurements of coastal change, including comparisons with the 1997–98 classic El Niño. As SLR accelerates and the magnitude and frequency of storms in midlatitudes potentially increase, coastal impacts such as those forced by the 2009–10 El Niño may become more common. Therefore, it is critical to develop a more detailed understanding of high-energy beach response to anomalous forcing conditions to enable more reliable predictions of coastal evolution under a changing and variable climate.

2. Study Area and Methods

[5] Comprehensive beach morphology monitoring programs spanning 5–13 years have been established in California, Oregon, and Washington (Figures 1a–1f). The monitoring programs employ Real-Time Kinematic Differential Global Positioning Systems (RTK-DGPS) mounted to a variety of mobile platforms to assess seasonal beach volume and/or cross-shore profile evolution [e.g., *Ruggiero et al.*, 2005] due to changes in ocean waves and water levels. In addition, the monitoring data are supplemented by aerial lidar surveys conducted in October 1997, April 1998, and October of 2002 along the U.S. West Coast. The relative position of shoreline proxies (i.e., the location of a particular elevation contour) and changes in beach elevation (or volume) are the primary metrics utilized to assess beach topographic change, with the two metrics significantly correlated for this study ($n = 111$, $R^2 = 0.8$, $p = < 0.0001$). Herein we focus on changes in elevation-based shoreline proxies, including the mean absolute shoreline position relative to the mean of all surveys and the mean maximum seasonal shoreline change (i.e., the winter shoreline retreat) to assess the coastal impact of the 2009–10 El Niño Modoki within each region relative to the entire time series of coastal changes. Along the 238 km of measurements (representative of the 2,000 km length of the U.S. West Coast), the mean shoreline behavior is determined by assimilating the results for hundreds of representative cross-shore profiles from beaches within each region: Southern California (5.2 km alongshore, 50 profiles from 2 surface maps), Central California (21 km alongshore, 1,107 profiles from 3 surface maps), Northern California (7 km alongshore, 130 profiles from one surface map), Oregon (40 km alongshore, 40 profiles), and the Columbia River Littoral Cell (165 km alongshore from 52 profiles augmented by 15 surface maps spanning 60 km) For reach region, given the uncertainty of RTK-DGPS-derived shoreline elevations (±0.05 m), and foreshore slopes ($\tan\beta \sim = 0.05$, range 0.02 to 0.08) along the U.S. West Coast, the uncertainty of the calculated change between any two shoreline positions is typically ~2 m, ~an order of magnitude smaller than the seasonal variability observed at most locations. See auxiliary material for additional details on the study areas and methods.[1]

3. Wave and Water Level Conditions

[6] Previous research along the U.S. West Coast documents that seasonal variability in shoreline change (sub-aerial beach volume) is highly correlated to seasonal variability in water levels and the wave climate [e.g., *Ruggiero et al.*, 2005; *Hansen and Barnard*, 2010], with the impact of individual storm events often masked. Therefore, we focus here on anomalies of the hydrodynamic forcing conditions relative to long-term seasonal mean values to improve our understanding of the observed beach changes during the 2009–10 El Niño.

[7] The influence of the 2009–10 El Niño event on the North Pacific winter wave climate is illustrated by Figure 1g, which shows the mean winter (1 October through 30 March) wave-energy flux (watts/m) calculated at four separate buoys offshore of the respective survey regions (one represents the PNW) relative to the mean winter wave-energy flux since each buoy was deployed. While only three of the four buoys analyzed fully captured the previous major El Niño event in 1997–98, the results broadly show that 2009–10 was the only winter since 1997–98 in which the wave-energy flux throughout California was ~20% above the mean. The PNW was notably less energetic, only ~5% above normal, however, the average of the highest 5% of the winter wave-energy flux measurements are similar across all regions for both the 1997–98 and 2009–10 El Niños. The data show that the 2009–2010 relative increase in winter wave energy was preceded by a relative decrease in energy during the 2008–09 winter (~30% below normal), the least energetic winter on record at all sites.

[8] The 2009–10 El Niño was also characterized by an anomaly in the winter mean wave direction, the magnitude of which was only eclipsed by the 1997–98 event (Figure 1h). There was a southerly shift of winter wave approach (except in Southern California) during winter 2009–10 of between 2° and 4° while during the 1997–98 El Niño the southerly shift was between 5° to more than 6° at the Pt. Reyes and Grays Harbor buoys, respectively. Conversely, in Southern California the 2009–10 winter mean wave direction shifted dramatically to the north by 6°, equivalent to 1997–98. However, the mean wave direction associated with the largest 5% of wave-energy flux measurements featured a southerly anomaly.

[9] The winter mean water level anomaly (Figure 1i), in 2009–10 exceeded the mean at all four locations and was collectively the second highest positive anomaly since the early 1990s, albeit dwarfed by the 1997–98 El Niño. The

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047707.

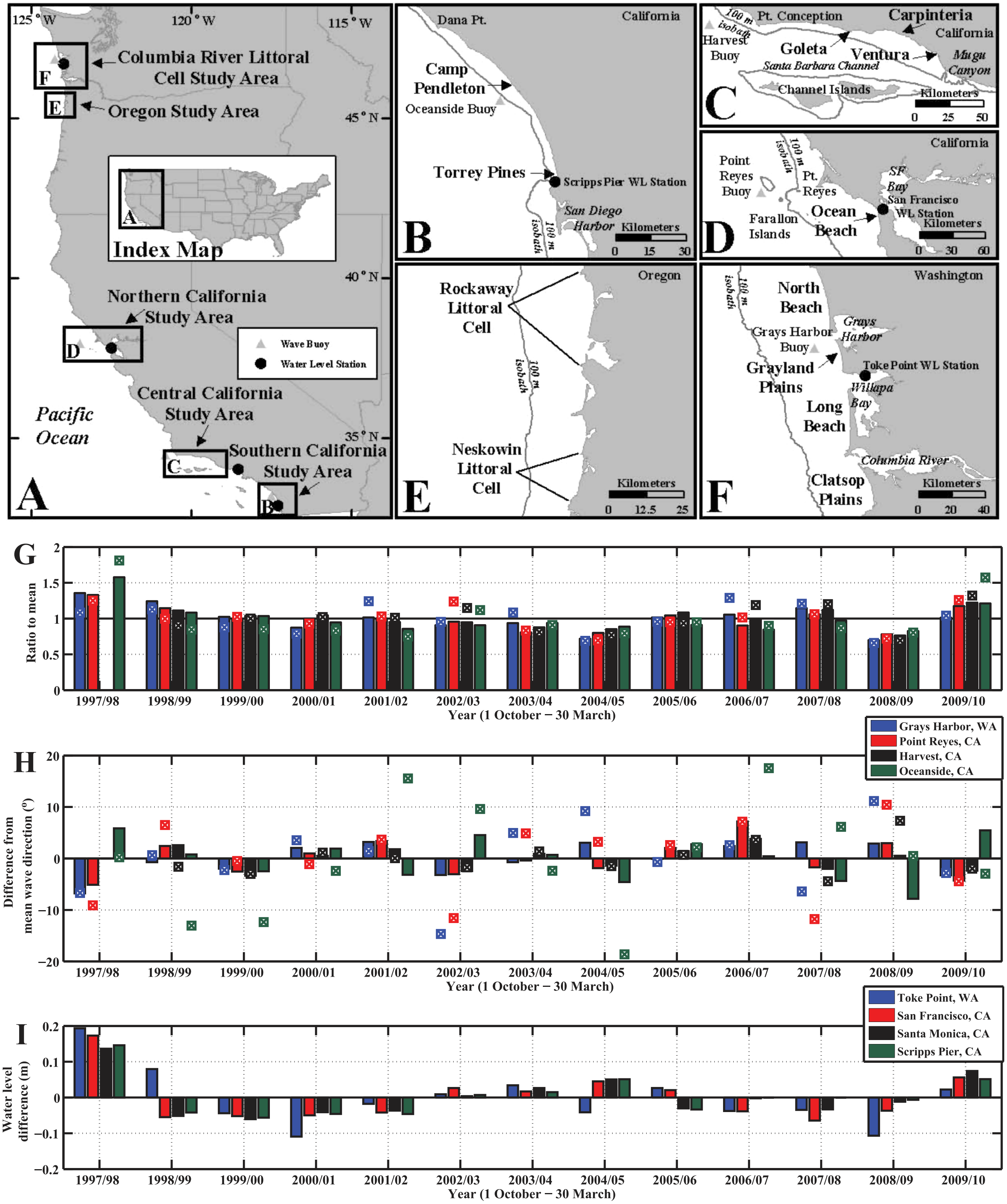

Figure 1. Study area and hydrodynamic forcing. (a–f) The location of the monitoring programs, water level (WL) stations [*NOAA*, 2011a], and wave buoys [*Scripps Institution of Oceanography*, 2011]. (g) Winter mean wave-energy flux normalized by the winter mean since each buoy's deployment. The ratio of the top 5% of the winter wave-energy flux relative to the mean of all winters is plotted with squares. (h) Divergence of winter mean peak wave direction (+ is North, − is South) from the winter mean. The wave direction divergence for the top 5% of the winter wave-energy flux measurements from Figure 1g are plotted with squares. (i) Divergence of winter mean water level anomaly from the winter mean of all years since 1995. The color bars in Figure 1g–1i correspond to each region: blue = PNW (Oregon and the Columbia River Littoral Cell), red = Northern California, black = Central California, and green = Southern California.

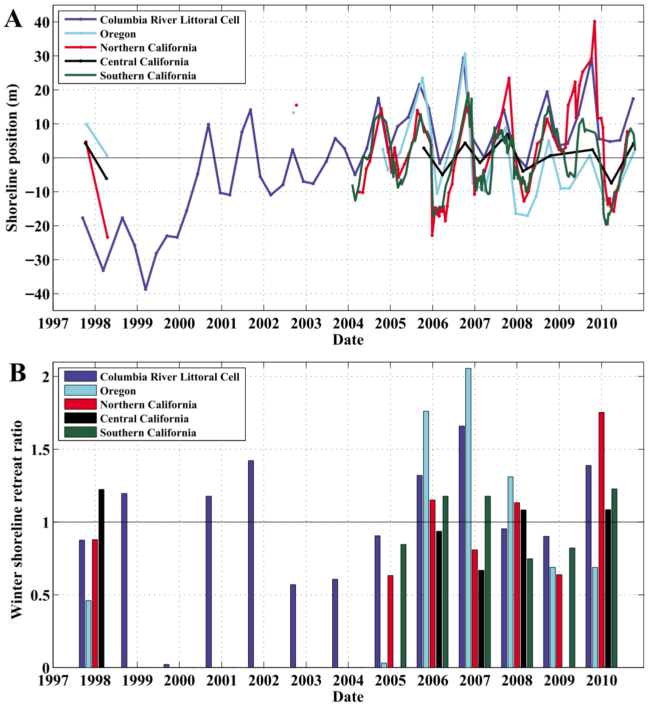

Figure 2. Coastal response. (a) Mean shoreline position relative to the mean of all surveys in each region. (b) The winter shoreline retreat relative to the mean winter retreat for all years.

winter water level anomaly was particularly high in California, where it averaged ~+7 cm.

4. Coastal Response to the 2009–10 El Niño

[10] The morphological response of the U.S. West Coast beaches to the anomalous forcing associated with the 2009–10 El Niño is synthesized in Figure 2. The shoreline retreated 23% more than the average winter for all regions, with the mean winter retreat exceeded (9 to 75% higher) in each region except for Oregon, including 36% for the three California regions. Despite the mild winter of 2008–09, the 2009–10 El Niño winter produced the most receded shoreline position and greatest winter shoreline retreat (23% greater than the mean) in the Southern California (Figure 1b) survey record.

[11] In Central California (Figure 1c) the powerful 2009–10 El Niño also forced the region's shoreline position to its most eroded state since beach observations commenced, eclipsing the impact of the 1997–98 El Niño. At the Ventura study site the mean beach elevation experienced twice as much beach lowering when compared with previous winters. In Carpinteria the beach eroded ~80% more during the 2009–10 El Niño than during the prior winters as measured by both mean elevation and shoreline position.

[12] Further north at Ocean Beach in Northern California (Figure 1d), severe erosion during the 2009–10 winter caused considerable public infrastructure damage, including the collapse of one lane of a major roadway, leading to a $5 million emergency remediation project. The winter shoreline retreat of 56 m was 75% greater than the mean and twice that observed in 1997–98. Beach recovery was poor through the fall of 2010, with the shoreline located well landward of pre-El Niño positions, leaving the beach and adjacent infrastructure highly exposed to subsequent winter storms. Conversely, lower wave energy levels during the 2008–09 winter allowed the shoreline to prograde ~25 m farther seaward than normal in the fall of 2009 (Figure 2a), which provided additional protection against the extreme erosion during the 2009–10 El Niño, probably limiting the infrastructure damage.

[13] Winter shoreline retreat on the Oregon coast (Figure 1e) was relatively subdued over the 2009–10 winter (13.3 m), particularly as compared to the winters of 2005–06 (34.0 m) and 2006–07 (39.7 m), but still managed to exceed the retreat measured over the 1997–98 El Niño (8.9 m). Although no significant damage was observed to infrastructure over the 2009–10 storm season, significant erosion due to more oblique wave approach did occur at a few discrete locations on the Oregon coast, especially to the north of rocky headlands and jetties (Figure 3a), and along creek mouths which shifted to the north.

[14] In the Columbia River Littoral Cell (CRLC) along the northwest Oregon and southwest Washington coast (Figure 1f), the 2009–10 winter shoreline retreat (24.5 m) eclipsed both the 1997–98 El Niño (15.5 m) and the 1998–99 La Niña (21.1 m) (Figure 2b), another significant climate anomaly which also featured large waves in the PNW. As in the Oregon region, the maximum winter shoreline retreat was also observed in the 2006–07 winter (29.3 m), a phenomena that is not associated with pronounced mean winter wave energy/direction or water level anomalies, but rather with the highest recorded mean of the upper 5% of wave-energy flux on record for the PNW (Figures 1g–1i). Also noteworthy is the extremely poor recovery of the CRLC shoreline through the summer of 2010 (similar to Northern California), with the shoreline located 15 m landward of the prior year's seaward maximum (Figures 2a and 3b), leaving the CRLC coast particularly vulnerable to the ensuing winter. The poor recovery can be partially explained by the mean annual wave energy anomaly at the Grays Harbor buoy compared to the winter values: larger than normal wave energy persisted through the spring and summer, placing 2009–10 as the 2nd most powerful wave energy year on record in the PNW. Based on the winter wave energy anomaly alone, 2009–10 ranks 6th.

5. Wave Directionality

[15] During both the 1997–98 and 2009–10 El Niños, the beaches north of headlands, jetties, and tidal inlets in the PNW were often severely eroded due to wave direction anomalies that produced higher than typical annual net-northward sediment transport (Figure 3). This is particularly apparent in Oregon (Figure 3a), which experienced significant erosion immediately north of the Tillamook and Nehalem Bay jetties. Furthermore, within both littoral cells, there is a general shift of sediment to the north or a progressive decrease in erosion to the north. In the CRLC, ~105 m of shoreline retreat during 2009–10 destroyed a road north of the entrance to Willapa Bay (southern end of the Grayland Plains sub-cell, Figure 3b), a very similar response to erosion observed in 1997–98. The pattern

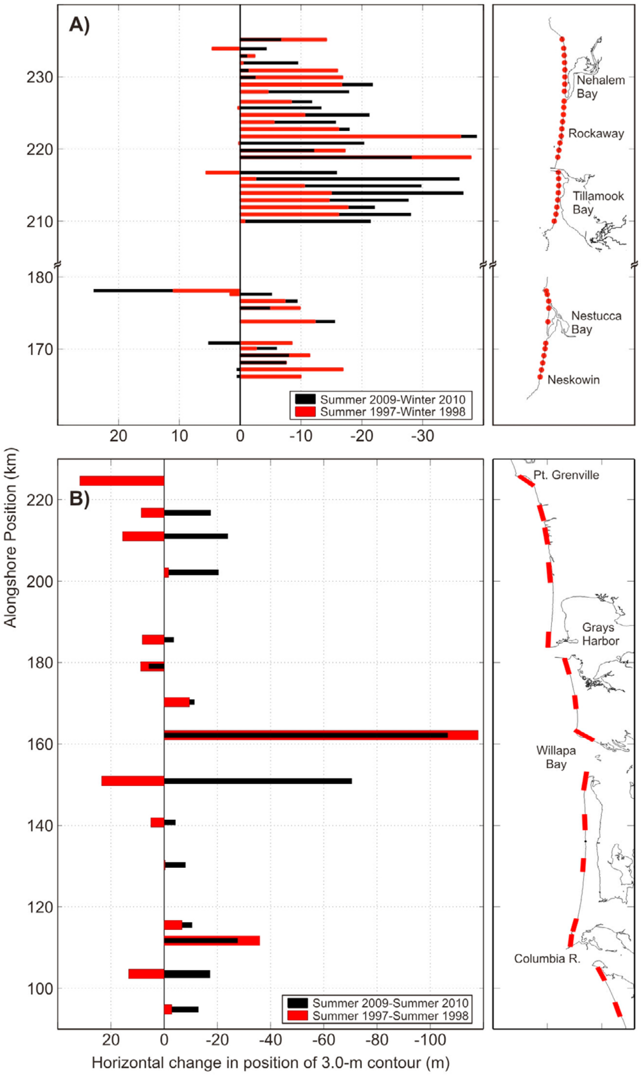

Figure 3. Effects of wave directionality in the Pacific Northwest in 1997–98 and 2009–10. (a) Mean winter shoreline change on the Oregon coast, and (b) mean annual shoreline change in the CRLC.

diverges in the northern ends of the CRLC sub-cells, where accretion dominated in 1997–98 (shoreline re-orientation [*Ruggiero et al.*, 2005]) and large erosion signals were recorded in 2009–10. A heightened annual wave energy anomaly in 2009–10 coupled with a less dramatic wave direction anomaly than 1997–98, may be responsible for this pattern which suggests relatively less alongshore transport and more offshore-directed transport than in 1997–98. In fact, *Ruggiero et al.* [2010b] could not reproduce the patterns of alongshore transport necessary to cause the 1997–98 observed changes with a one-line shoreline change model without the inclusion of a sediment sink accounting for significant cross-shore losses. The increase in offshore-directed sediment transport relative to normal conditions was probably the result of both wave height and water level anomalies. Therefore, both model results and morphology change measurements suggest that while strong gradients in alongshore transport are necessary to force the (1997–98) observed sub-cell shoreline re-orientation, the overall morphological changes associated with both of the El Niño events was the result of a combination of cross-shore and alongshore processes.

6. El Niño Forcing Styles and Implications for Observed Coastal Response

[16] The CP-El Niño (El Niño Modoki) of 2009–10 was the strongest of this newly identified climate event on record, part of an increase in the intensity of central equatorial events over the last three decades [*Lee and McPhaden*, 2010]. Other recent CP-El Niños occurred in 2002–03 and 2004–05, both associated with a general shift to more southerly wave approaches and higher winter water levels on the U.S. West Coast, although with relatively mild wave energy compared to 2009–10 (see Figures 1g–1i). Notably, the recent CP-El Niños (2002–03, 2004–05 and 2009–10) are characterized by a distinct south-north gradient of decreasing anomalies for wave energy (Figure 1g) and water levels (Figure 1i), providing evidence for a latitudinal dependence on oceanographic forcing. Further, the winter beach response anomaly during the 2009–10 CP-El Niño is clearly less severe at the higher latitude PNW study regions, while the California beaches experienced extreme shoreline retreat (Figure 2).

[17] In comparison to EP-El Niños (classic El Niños), lower SST anomalies, and the associated reduced rates of tropical convection, decrease the atmospheric teleconnections of the CP-El Niños to higher latitudes [*Kug et al.*, 2009; *Behera and Yamagata*, 2010], implying that anomalously high sea levels and wave energy associated with EP-El Niños may be tempered on the U.S. West Coast under CP-El Niños. Certainly the EP-El Niño of 1997–98 resulted in significantly higher than average winter wave energy and water levels along the entire U.S. West Coast (Figures 1g and 1i), while only the three California study regions experienced abnormally high mean winter wave energy during the 2009–10 CP-El Niño.

[18] Winter shoreline retreat is significantly correlated to the mean winter ($n = 18$, $R^2 = 0.27$, $p = 0.026$) and top 5% ($n = 18$, $R^2 = 0.30$, $p = 0.019$) of wave-energy flux measurements in California, whereas in the PNW shoreline retreat is only significantly correlated with the top 5% of wave-energy flux measurements ($n = 20$, $R^2 = 0.27$, $p = 0.019$). Winter shoreline retreat is not correlated with more extreme metrics of wave energy (e.g., top 1%) for any region. High winter wave energy is linked to the Multivariate ENSO (MEI) Index, with the El Nino events of 1982–3, 1997–98 and 2009–10 standing apart from all other years on the U.S. West Coast (Figure 4).

[19] *Behera and Yamagata* [2010] link the large decadal background of CP-El Niños to central Pacific sea level rise, which in turn influences the U.S. West Coast through atmospheric teleconnections, whereas EP-El Niños are characterized by interannual variability. Therefore, the extended period of elevated wave-energy conditions in 2009–10, along with the southerly shift in the predominant wave approach angle was sufficient to modify cross-shore and alongshore sediment transport patterns that resulted in significant changes in the morphology of the beaches, and limited spring/summer beach recovery in Northern

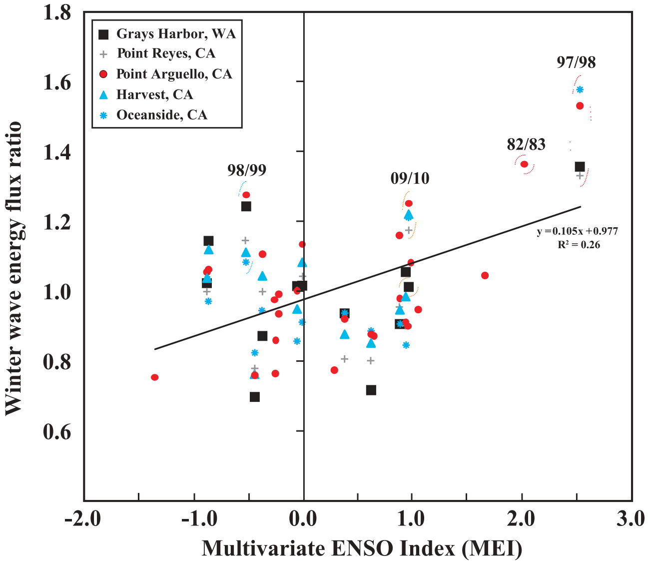

Figure 4. Winter mean wave-energy flux normalized by the winter mean versus MEI Index. The trend line (n = 71, R = 0.51, p = < 0.001) is for the Pt. Arguello non-directional wave buoy [*NOAA*, 2011b] the only buoy record that includes the 1982–83 El Niño. The buoy is located 36 km northwest of the Harvest wave buoy (see Figure 1c).

California and the PNW (Figures 2a and 3b). If the intensity of CP-El Niños continues to increase, as has occurred in recent decades, the impacts to U.S. West Coast beaches may become more broadly severe both seasonally and inter-annually, as was demonstrated during 2009–10. Nevertheless, while there is a relatively good understanding of the effects of EP-El Niños on regional climate, work is ongoing to better define the ocean and atmospheric dynamics associated with CP-El Niño [e.g., *Yeh et al.*, 2011]. The continuation of long-term monitoring programs along the U.S. West Coast will help link the impact of climatic phenomena such as CP-El Niños with remote coastal response, especially critical as rapid global climate changes are occurring that will strongly influence the coupled ocean-atmospheric system.

7. Conclusions

[20] Coastal erosion during the 2009–10 El Niño was substantial along California beaches, where observations of winter shoreline retreat exceeded the mean by 36%, and absolute shoreline positions were pushed close to or beyond recent recorded landward extremes. Winter shoreline retreat in the PNW exceeded that observed during the El Niño of 1997–98 but was tempered in comparison to several non-El Niño years. Elevated wave energy levels that persisted through spring and summer 2010 limited beach recovery on many U.S. West Coast beaches. Observed extreme shoreline retreat in the southern ends of PNW littoral cells or sub-cells is linked to wave direction anomalies, a typical El Niño pattern. The variability in beach retreat observed along U.S. West Coast beaches during the 2009–10 winter is shown to be a response to the central equatorial El Niño (El Niño Modoki), characterized by forcing patterns that contrast with the classic El Niño, including latitudinal gradients in wave energy, wave direction, and water level anomalies.

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J. Allan, Coastal Field Office, Oregon Department of Geology and Mineral Industries, PO Box 1033, Newport, OR 97365, USA.

P. L. Barnard, Pacific Coastal and Marine Science Center, U.S. Geological Survey, 400 Natural Bridges Dr., Santa Cruz, CA 95060, USA. (pbarnard@usgs.gov)

A. Doria, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093, USA.

J. E. Hansen, Department of Earth and Planetary Sciences, University of California, 1156 High St., Santa Cruz, CA 95064, USA.

G. M. Kaminsky, Coastal Monitoring and Analysis Program, Washington State Department of Ecology, PO Box 47600, Olympia, WA 98504, USA.

P. Ruggiero, Department of Geosciences, Oregon State University, Corvallis, OR 97331, USA.