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**Key Points:**

- The 2009–2010 and the present 2015–2016 El Niños have similar theoretical potential for wave-driven, shoreline erosion in Southern California
- Three beaches nourished in 2012 are now elevated above 2009–2010 levels. An unnourished beach is now eroded slightly below 2009–2010 levels
- Observations of nourishment longevity, including the role of grain size, are important for coastal engineers and planners

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# Mid-El Niño erosion at nourished and unnourished Southern California beaches

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**Abstract** Wave conditions in Southern California during the 2015–2016 El Niño were similar to the 2009–2010 El Niño, previously the most erosive (minimum beach widths and subaerial sand levels) in a 7 year record. As of February 2016, Torrey Pines Beach had eroded slightly below 2009–2010 levels, threatening the shoulder of a major highway. However, Cardiff, Solana, and Imperial Beaches, nourished with imported sand in 2012, were on average 1–2 m more elevated and more than 10 m wider than in 2009–2010. Monthly subaerial sand elevation observations showed that the nourished beaches remained consistently wider than unnourished beaches under similar wave conditions. In contrast to a 2001 nourishment at Torrey Pines built with native sized sand that was removed from the beach face during a single storm, these relatively coarse grained nourishments protected shorelines for several years, and during the significant wave attack of the 2015–2016 El Niño, as of February 2016.

## 1. Introduction

California's wave climate and beaches are altered substantially by the El Niño Southern Oscillation (ENSO), with greater wave energy flux and erosion during the warm phase El Niño [*Dingler and Reiss*, 2002; *Sallenger et al.*, 2002; *Barnard et al.*, 2011, 2015; *Revell et al.*, 2011]. While Pacific coastal regions are threatened by predicted long-term relative sea level rise averaging half a meter by the end of the century [*Carson et al.*, 2016], ENSO is superimposed on this long-term trend, modifying regional coastal sea levels by a few decimeters on interannual time scales [*Enfield and Allen*, 1980; *Huyer and Smith*, 1985; *Ryan and Noble*, 2002; *Hamlington et al.*, 2015]. Most significantly, ENSO modulates the locations of storms responsible for large wave events [*Allan and Komar*, 2006; *Barnard et al.*, 2015] that can raise nearshore water levels through wave setup by a meter or more [*Longuet-Higgins and Stewart*, 1962; *Bowen et al.*, 1968; *Guza and Thornton*, 1981]. Furthermore, regions exposed to anomalously energetic wave conditions experience intensified beach erosion, compounding flood risk and potentially depressing multibillion dollar tourist economies [*Pendleton et al.*, 2011; *WorleyParsons*, 2013; *Alexandrakis et al.*, 2015]. The 1982–1983 and 1997–1998 El Niños were the highest sea surface temperature anomalies in the eastern equatorial Pacific since 1950, and the 2015–2016 El Niño ranks alongside them [*Climate Prediction Center*, 2016]. Seven years of hourly wave data and monthly sand levels at Torrey Pines Beach, CA, show that the winter 2015–2016 conditions in Southern California are similar to the moderate 2009–2010 El Niño. As of 29 February, 2015–2016 winter significant wave heights had exceeded 2 m for 364 h, comparable to the 360 h of exceedance by 28 February of winter 2009–2010. (Non-El Niño winters totaled less than 200 h of 2 m exceedance.) Furthermore, at Torrey Pines the 2015–2016 beach was slightly narrower, and subaerial sand levels were slightly lower than in 2009–2010.

Imported sand, mechanically placed on the beach, modifies the impact of the 2015–2016 El Niño at the other monitored sites. This coastal management technique, known as beach nourishment, widens and elevates the beach to mitigate flooding and erosion and promotes tourism and recreation. "Soft" sand-based coastal management techniques (e.g., beach nourishment, shore nourishment [*Hamm et al.*, 2002], and scraped berms [*Gallien et al.*, 2015]) are often preferred to hard structures (e.g., groins, jetties, breakwaters) that can stifle the sediment supply to adjacent coastlines [*Bruun*, 1995]. Beach nourishment is a primary erosion mitigation strategy worldwide, and nonopportunistic placements (placements not benefiting from sand available from a preexisting project, e.g., a harbor dredging) are expensive [*Clayton*, 1991; *Haddad and Pilkey*, 1998; *Trembanis and Pilkey*, 1998; *Valverde et al.*, 1999; *Hanson et al.*, 2002; *Cooke et al.*, 2012; *Luo et al.*, 2015].

The wave-driven redistribution of beach nourishment sand is an important component of the complex cost-benefit analysis, but is poorly understood. On the U.S. Gulf and East Coasts, hurricanes most significantly

**Table 1.** Beach Statistics

| Beach | Mean Beach Width (m) | Survey Alongshore Span (km) | Nourishment Alongshore Span (km) | Reported 2012 Nourishment Volume ($m^3$)[a] | Reported Nourishment Grain Size (mm)[a] | Native Grain Size (mm)[b] |
|---|---|---|---|---|---|---|
| Cardiff | 43 | 1.7 | 0.5 | 68,000 | 0.57 | 0.16 |
| Solana | 28 | 2.5 | 0.5 | 107,000 | 0.55 | 0.15 |
| Torrey | 38 | 3.1 | - | - | - | 0.23 |
| Imperial | 58 | 4.1 | 1.5 | 344,000 | 0.53 | 0.25 |

[a] *Coastal Frontiers* [2015].
[b] At MSL, Cardiff, Torrey, and Imperial are from *Ludka et al.* [2015]. Solana is from *Group Delta Consultants* [1998].

redistribute nourishments [*Browder and Dean*, 2000; *Gares et al.*, 2006; *Elko and Wang*, 2007]. However, on the U.S. West Coast, tropical storms are rare and extreme erosion is dominated by repeated storms during El Niño [*Barnard et al.*, 2015]. *Elko et al.* [2005] report increased nourishment erosion rates on the U.S. Gulf Coast during the 1997–1998 winter El Niño. Our detailed observations of nourishment influence in the more severely affected Southern California, during the 2015–2016 El Niño, are unique.

In 2001, approximately 1.6 million $m^3$ of sand was placed on 12 San Diego County beaches [*Coastal Frontiers*, 2015] at a total cost of \$17.5 million, the first nonopportunistic nourishments in the region [*Griggs and Kinsman*, 2016]. The entire Torrey Pines pad, constructed with a sand grain size similar to native, washed offshore in a single storm [*Seymour et al.*, 2005], partially returned to the beach face the following summer, and then became too dispersed to track [*Yates et al.*, 2009]. An additional 1.15 million $m^3$ of sand was placed on eight San Diego County beaches in 2012 [*Coastal Frontiers*, 2015] at a total cost of \$28.5 million [*Griggs and Kinsman*, 2016]. Based on comparatively sparse observations that included all the nourishments [*Coastal Frontiers*, 2015], *Griggs and Kinsman* [2016] stated that "Overall, the sand added to the relatively narrow San Diego County beaches (during the 2001 and 2012 nourishment campaigns) had a very short life span on the exposed subaerial beach." We present uniquely comprehensive observations showing that the impacts of three of the relatively coarse-grained nourishments placed in 2012 (Table 1) have remained detectable on the beach face for several years and maintained a more seaward shoreline during the 2015–2016 El Niño than the 2009–2010 El Niño. February 2016 photos show the extreme erosion at Torrey Pines, unnourished since 2001 (Figure 1b), compared with Cardiff and Imperial Beaches, both nourished in 2012 (Figures 1a and 1c).

## 2. Wave Observations

Waves are characterized with observations from the Torrey Pines Datawell directional wave buoy (NDBC 46225), located 12 km offshore of Torrey Pines Beach in 550 m water depth. A few gaps in the observations during low waves (3% of the total record) are filled with a regional wave model. Although waves differ between the beaches [*Ludka et al.*, 2015], wave observations at the Torrey Pines buoy are broadly representative. Waves are seasonal, with relatively low waves in summer (e.g., zero occurrences of wave heights above 2 m, Figure 2b). Winter wave heights are larger and elevated above 2 m most often during the 2009–2010 and 2015–2016 El Niños. The maximum wave height of 5.5 m was observed on 1 February 2016.


**Figure 1.** Low-tide photos at (a) Cardiff, (b) Torrey Pines, and (c) Imperial Beach on 25 February 2016. Cardiff and Imperial Beaches, nourished in 2012, were relatively sandy and wide. Torrey Pines, unnourished since 2001, was primarily cobble, narrow, and backed by the eroding shoulder of Hwy 101.

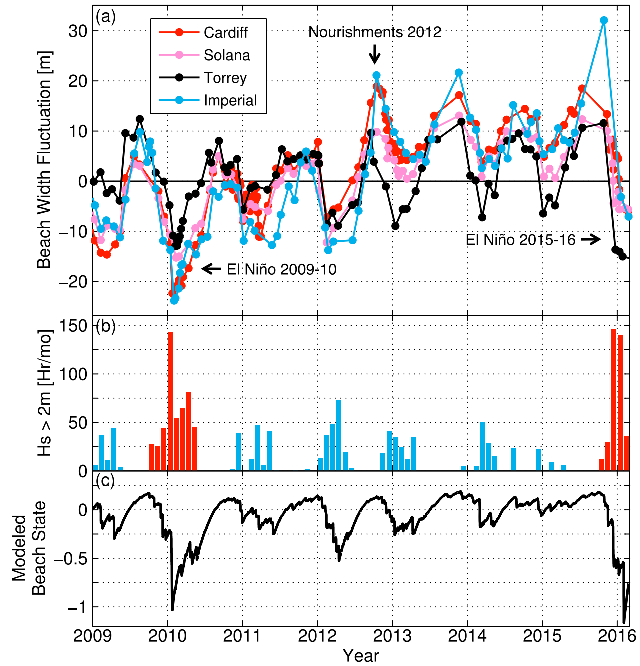


**Figure 2.** (a) Beach width fluctuation (about the mean, Table 1) versus time for four Southern California beaches (legend). Each dot is an average over several kilometers alongshore (Table 1 and Figure 3). (b) Hours per month the observed significant wave height (*Hs*) exceeded 2 m (combined swell and seas, 0.04–0.25 Hz) at the Torrey Pines buoy (NDBC 46225) versus time. Red indicates El Niño winters. (c) Beach state estimated using observed waves and published model coefficients [*Ludka et al.*, 2015]. The model, insensitive to initial conditions after a brief transient, is initialized with $A = 0$ on 1 January 2009.

A simple 1-D beach state model [*Ludka et al.*, 2015] based on an equilibrium beach hypothesis [*Wright and Short*, 1984; *Wright et al.*, 1985] previously calibrated on these beaches characterizes the erosion potential of the observed waves, providing a comparison of different winters. The instantaneous beach state change rate, $\mathrm{d}A/\mathrm{d}t$, is assumed proportional to the instantaneous energy $E$ and energy disequilibrium $\Delta E$

$$\frac{\mathrm{d}A}{\mathrm{d}t} = C^{\pm}E^{1/2}\Delta E \tag{1}$$

where $C^{\pm}$ are empirical change rate coefficients for beach face accretion ($C^{+}$ for $\Delta E < 0$) and erosion ($C^{-}$ for $\Delta E > 0$). The factor $E^{1/2}$ insures small changes in $A$ when $E$ is small. The sign of $\mathrm{d}A/\mathrm{d}t$ is determined by the sign of the energy disequilibrium,

$$\Delta E = E - E_{\mathrm{eq}}, \tag{2}$$

where

$$E_{\mathrm{eq}} = aA + b. \tag{3}$$

For a given beach state, $A$, the equilibrium energy $E_{\mathrm{eq}}$ is the wave energy that causes no profile change. Using modeled hourly waves at each site, and sand levels that excluded nourishments, reef, canyon, and shoal sections of beach, the best fit model for free parameters ($C^{\pm}$, $a$, and $b$) are similar on these beaches. A single set of optimized free parameters for alongshore uniform sandy reaches at all study beaches reasonably predicts profile evolution [*Ludka et al.*, 2015].

Waves at the Torrey Pines buoy are used with existing optimized equilibrium model parameters to solve (1) and (2) for the beach state, $A$ (Figure 2c), quantifying the time-integrated wave erosion potential and neglecting site specific effects including beach nourishments, bedrock, cliffs, self-armoring of the eroded beach with cobbles, and riprap bordering Hwy 101. Modeled beach face erosion was extreme during the 2009–2010 El Niño ($A = -1.03$) and was exceeded ($A = -1.17$) on 2 February 2016 (Figure 2c), suggesting that the 2015–2016 El Niño had more erosion potential than the 2009–2010 El Niño.

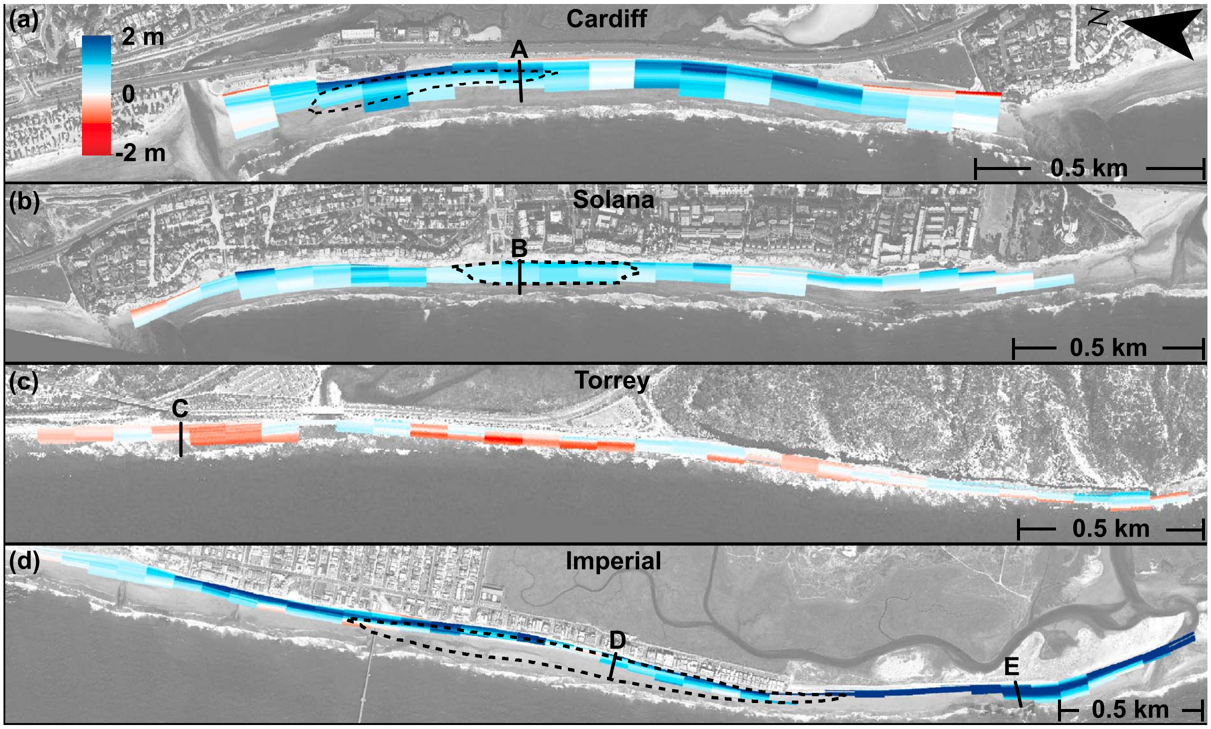


**Figure 3.** Sand elevation differences (color bar) between the winter 2016 and 2010 surveys with minimum beach widths. (a) Cardiff 23 February 2016 relative to 12 February 2010, (b) Solana 23 February 2016 relative to 12 February 2010, (c) Torrey Pines 27 January 2016 relative to 8 February 2010, and (d) Imperial 25 February 2016 relative to 2 February 2010. Horizontal scale (bottom right) changes with panel. Black dotted lines outline the 2012 nourishment placement regions at Cardiff, Solana, and Imperial Beaches. (c) Torrey Pines, unnourished since 2001, has the smallest elevation difference, mostly less than 0.5 m of relative erosion (red). (d) Imperial Beach received the most imported sand in 2012 and almost the entire subaerial beach is elevated 1–2 m above the 2010 El Niño survey. Cardiff and Solana are elevated above 2010 by about 1 m. Black lines mark the locations of transect locations A–E in Figure 4.

## 3. Sand Level Observations

Subaerial sand elevations at four San Diego County beaches were monitored monthly at low tide with a GPS-equipped vehicle [*Seymour et al.*, 2005] driving shore-parallel tracks with ~10 m spacing. Quarterly beach and bathymetry surveys have 100 m shore-perpendicular transects, but only the subaerial portions of these surveys are considered in this analysis. Alongshore survey spans vary between 1.7 and 4.1 km depending on the site (Table 1 and Figure 3). During the monitoring, three beaches were nourished with between 68,000 and 344,000 m$^3$ of coarse-grained sand ($D_{50}$ ~ 0.5–0.6 mm), over subaerial alongshore spans between 500 and 1500 m (Table 1, dotted black lines in Figure 3).

Temporal fluctuations in beach width (Figure 2a) are estimated from changes in the cross-shore location of the mean sea level contour (MSL = +0.77 m NAVD88), averaged over the survey alongshore span. If a survey does not include observations of MSL on more than 2/3 of the alongshore span, it is not considered. Beach widths vary seasonally due to seasonal fluctuations in wave energy, with punctuated erosion during El Niño. On average, all four beaches were relatively narrow during the 2009–2010 El Niño. In February of 2016, Cardiff, Solana, and Imperial Beaches, nourished in fall 2012, were wider than 2009–2010 by 10 m or more. Torrey Pines, nourished in 2001 [*Seymour et al.*, 2005; *Yates et al.*, 2009], was eroded slightly below 2009–2010 levels.

Plan view sand level difference maps (Figure 3) between the 2016 and 2010 surveys with minimum beach width (observed as of February 2016, Figure 2a) show the subaerial beach was relatively elevated over the entire alongshore span at Imperial, Cardiff, and Solana Beaches. Relative sand levels were most elevated, by 1–2 m, at Imperial Beach, the site of the largest nourishment. Cardiff and Solana were elevated above 2010 by about 1 m. In contrast, at Torrey Pines, the subaerial beach was similar to, and in many locations slightly eroded relative to, 2009–2010 levels.

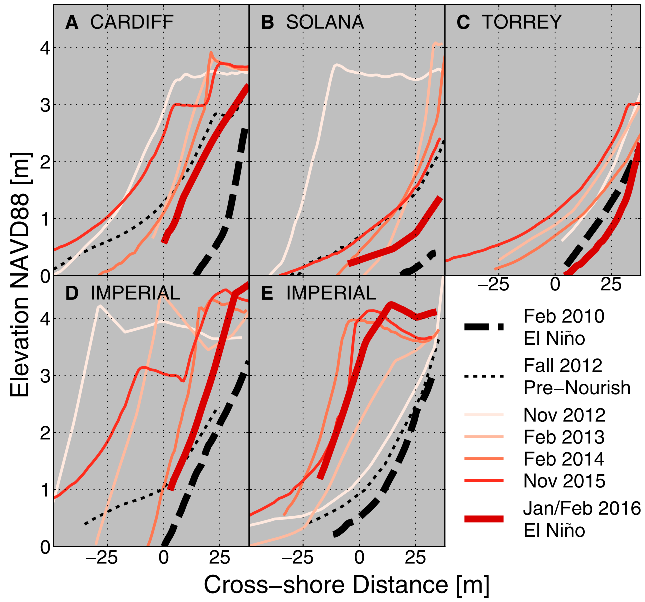


**Figure 4.** Sand level versus cross-shore distance at representative times (legend) at transects labeled in Figure 3. Erosion during the 2009–2010 El Niño was extreme (thick dashed black lines). The January 2016 profile (thick red line) at (c) Torrey is similar to February 2010, but at (a, b, d, and e) sites nourished in 2012, the February 2016 profile is elevated above February 2010. The prenourished profile is a thin black dotted line. At transects located in the original placement region (Figures 4a, 4b, and 4d), the nourished pad is evident in the November 2012 profile and retreats over time, with partial recovery in summer/fall as in November 2015 (Figures 4a and 4d). As the Imperial Beach nourishment pad retreated (Figures 4d), the southward region accreted (Figures 4e).

Cross-shore profile evolution at the 2012 nourishment sites corroborates that these beaches were wider and more elevated in 2015–2016 (thick red lines, Figures 4a, 4b, 4d, and 4e) than in the 2009–2010 El Niño (thick dashed black line, Figures 4a, 4b, 4d, and 4e). The fall 2012 nourishment widened and elevated the subaerial beach (compare thin black dotted prenourish and thin light orange November 2012 profiles, Figures 4a, 4b, and 4d). After placement, the pads retreated (Figures 4a, 4b, and 4d), with partial recovery in the summer months (November 2015, Figures 4a, 4d, and 2a). As the nourishment pads retreated (Figure 4d), adjacent regions accreted (Figure 4e). Alongshore transport was especially pronounced at Imperial Beach; the southern region (Figure 4e) became (perhaps surprisingly) more elevated relative to February 2010 levels than the original placement region (Figure 4d). In contrast, on 27 January 2016 (when $A = -0.57$, Figure 2c) Torrey Pines was eroded similar to 2009–2010 El Niño levels (Figure 4c).

## 4. Discussion and Conclusions

The 2015–2016 and 2009–2010 El Niños were the most energetic and erosive winters in the 7 year record from 2009 to 2016 in Southern California (black line Figure 2a, Figures 2b and 2c). Observations during extreme winters are essential to understand the impact of successive energetic storms on sand levels and the equally important recovery between storms. No existing numerical model accurately simulates erosion, recovery, and the potentially increased erosion resistance of the dense cobble layers (Figure 1b) often exposed on San Diego county beaches [*Ludka et al.*, 2015].

As future El Niños and rising sea levels threaten coastal infrastructure, coastal managers must decide whether to protect, accommodate, or retreat [*Nicholls*, 2011]. Beach nourishment is an important protection method worldwide, yet the wave-driven redistribution of nourishment sand is poorly understood. We observed three relatively coarse-grained nourishments that partially remained on the beach face for several years (Figures 4a, 4b, 4d, and 4e). This evolution differed dramatically from a 2001 Torrey Pines nourishment with approximately 160,000 m$^3$ of imported sand with grain size similar to the native $D_{50} \sim 0.2$ mm. This 500 m long subaerial pad of native grain size sand completely washed offshore during a single storm with an unexceptional maximum significant wave height of 3.2 m during a neap tide (1 m range) [*Seymour et al.*, 2005]. While these contrasting nourishment behaviors occurred on different Southern California beaches, these beaches have been shown to respond similarly to incident wave conditions when not influenced by nourishment [*Ludka et al.*, 2015]. Therefore, these results suggest that a larger than native grain size distribution is a primary factor in nourishment evolution in Southern California, as at sites with different wave climates [*Dean*, 1991; *Kana and Mohan*, 1998].

Of the 20 total San Diego County beach nourishments in 2001 and 2012, we monitored only four in detail. In total 2.75 million $m^3$ of sand was placed [*Coastal Frontiers*, 2015], with total cost of about $44 million [*Smith*, 2016]. Future nourishments in Southern California will be expensive (e.g., $160,000,000 over 50 years to nourish a several kilometer reach in San Diego County [*Diehl*, 2015]). Accurately assessing the evolution and impact of previous nourishment projects, in the context of long-term, high-resolution, large-scale monitoring, is essential. Based on comparatively sparse observations that included all the nourishments, *Griggs and Kinsman* [2016] concluded that "Most of the 2,600,000 $m^3$ sand added to the beaches of San Diego County during [the 2001 and 2012 nourishments] was essentially eroded from the exposed subaerial beach during the first year following nourishment." It should be anticipated that nourishment sand will leave the original placement region, and analysis should include the impact of the nourishment sand on the surrounding region over many years [*Stive et al.*, 2013; *de Schipper et al.*, 2016]. While the assessment by *Griggs and Kinsman* [2016] is consistent with the observed evolution of the native grain-sized 2001 Torrey Pines nourishment that completely washed offshore in a single storm [*Seymour et al.*, 2005], it does not consider that sand partially returned to the beach face the following summer [*Yates et al.*, 2009]. While much of the sand placed in 2012 was indeed eroded from the original placement regions in the first year, the back beach portions of the Cardiff and Imperial nourishment berms remained intact for several years (Figures 4a and 4d). Furthermore, much of the sand eroded from the original placement regions accreted adjacent subaerial regions (Figures 4d and 4e). Sand that was moved offshore in winters partially returned in summers. Notably, at Solana, Cardiff, and Imperial Beaches the (alongshore averaged) beach remained wider than prenourishment under similar wave conditions, including the energetic El Niño, observed as of February 2016 (Figure 2a).

The San Diego County nourishments were placed to increase tourism and recreation and reduce flooding and erosion. These public beaches are heavily used and include California State Beaches at Cardiff and Torrey Pines. The nourishments were expected to reduce Highway 101 closures at Cardiff and Torrey Pines by protecting it from flooding and erosion (Figure 1b). Owners and patrons of beachfront restaurants at Cardiff (Figure 1a) and homeowners at Imperial Beach (Figure 1c) desired protection from wave overtopping. Detailed monitoring is crucial in order to estimate the extent that these goals were achieved and to weigh the benefits against the monetary expense and potential negative ecological [*Speybroeck et al.*, 2006; *Baker*, 2016; *Wooldridge et al.*, 2016] and groundwater impacts [*Hargrove*, 2015]. Repetitive nourishments, perhaps augmented with retention structures, will be costly. Future El Niños, coupled with sea level rise, will inevitably increase pressure on already sparse sand resources [*Roelvink*, 2015]. Detailed monitoring of beach sand levels and storm damage over decades will be needed to inform coastal management during changing conditions.

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