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Supporting Information for

A Climatic Sand Management Model for Cardiff State Beach, CA

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Introduction

The supporting information provides equations and datasets that form the basis of the models outlined in the manuscript. The figures included here are examples of surveyed data for Cardiff, and how the observed beach changes relate to the Bruun rule.

Text S1. Cardiff Nearshore Sand Retention

Surveys of Cardiff from 2011-2015, between El Niños, show a significant increase in sediment volume that was equal to the reported additions to the beach by annual inlet bypassing and a beach nourishment project (Fig. 3, Table 1). This suggests that during non-El Niño years Cardiff can be approximated as either a static closed system or a dynamic sediment reservoir (or capacitor) with equal amounts of sediment naturally entering the system in the north and exiting in the south, independent of the human sand additions. Either scenario provides a useful basis for a data-driven climatic sediment budget model for the area.

Plausible explanations for sand retention at Cardiff include reefs at the southern boundary acting as a sand weir, limiting the southward annual drift through the area during non-El Niño years (Fig. S1), combined with weak annual wave-driven alongshore transport forcing seaward of the lagoon (Fig. S2).

It is generally accepted that waves move sand southward along the northern San Diego County coastline on interannual timescales, a process often referred to as the Oceanside Littoral Cell "river of sand" (Inman and Shelton, 1967; Patsch and Griggs, 2006). However, this southward migration of sand is likely episodic owing to the ENSO climate cycle that strongly influences the local winter wave climate (Smith and Barnard, 2021, Vos et al., 2023).

The SIO Coastal Data Information Program (CDIP) Monitoring and Prediction (MOP) system (O'Reilly et al., 2016) provides hourly hindcasts of nearshore wave heights (H_S) and radiation stresses (S_{xy}) for sites roughly 100 m apart on the 10-m depth contour along the Cardiff coastline. A widely used formula for longshore transport is the CERC equation (Shore Protection Manual, 1984; Seymour and Higgins, 1978). The transport rate (Q) is proportional to the square root of significant wave height times the longshore wave radiation stress:

(A.1) $Q = K \cdot \sqrt{H_s} \cdot S_{xy}$,

where the coefficient K is a function of grain size.

Leaving K as an unknown and summing a time series of hourly MOP Q values over a beach year yields a net annual *relative* transport rate at each alongshore site. Annual relative transport rates at Cardiff for the 2011-2016 beach years (Fig. S2) show a trend of decreasing southward annual transport in front of the lagoon and a mild (small positive) net transport reversal near Seaside Reef.

S_{xy} estimates in 10-m depth are considered valid in the actual shoreward littoral transport zone for the case of a simple planar beach (Longuet-Higgins, 1964). Therefore, the transport estimates at Cardiff are more qualitative owing to the complexity of the nearshore bathymetry around the reefs. Nevertheless, lower annual southward transport values are predicted in the vicinity of all the (less complex) coastal lagoons in the region and this may contribute to multi-year time periods of sand retention at Cardiff.

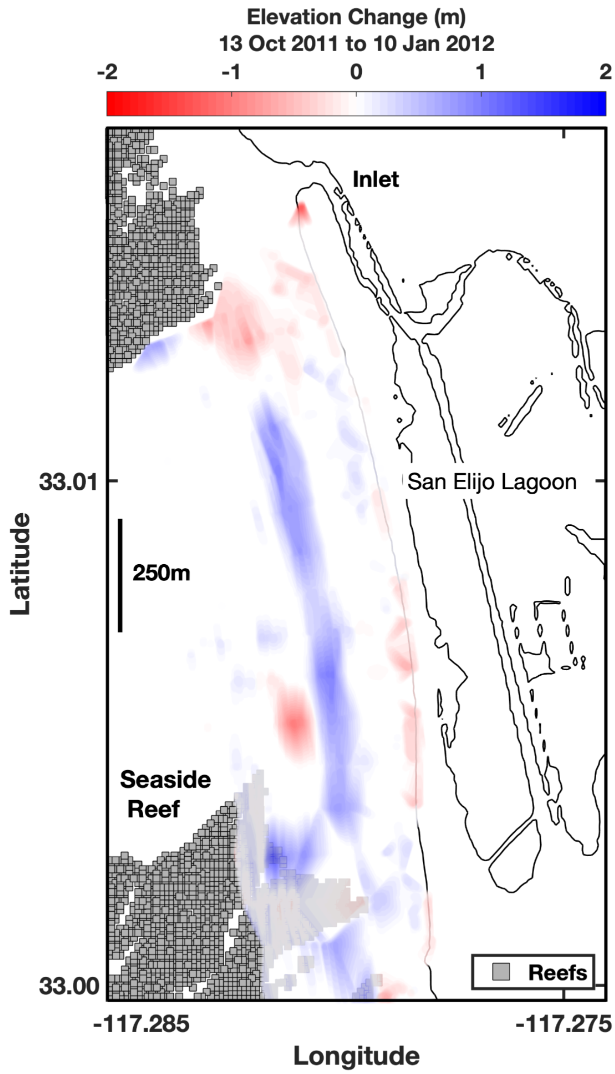

Figure S1. Example surveyed winter sand erosion and deposition pattern at Cardiff in the non-El Niño winter of 2012. Significant sand deposition (blue) occurs around the elevated Seaside Reef (gray area, bottom of figure), a physical barrier to southward drift, as is Tabletop Reef further to the south (Fig. 1c).

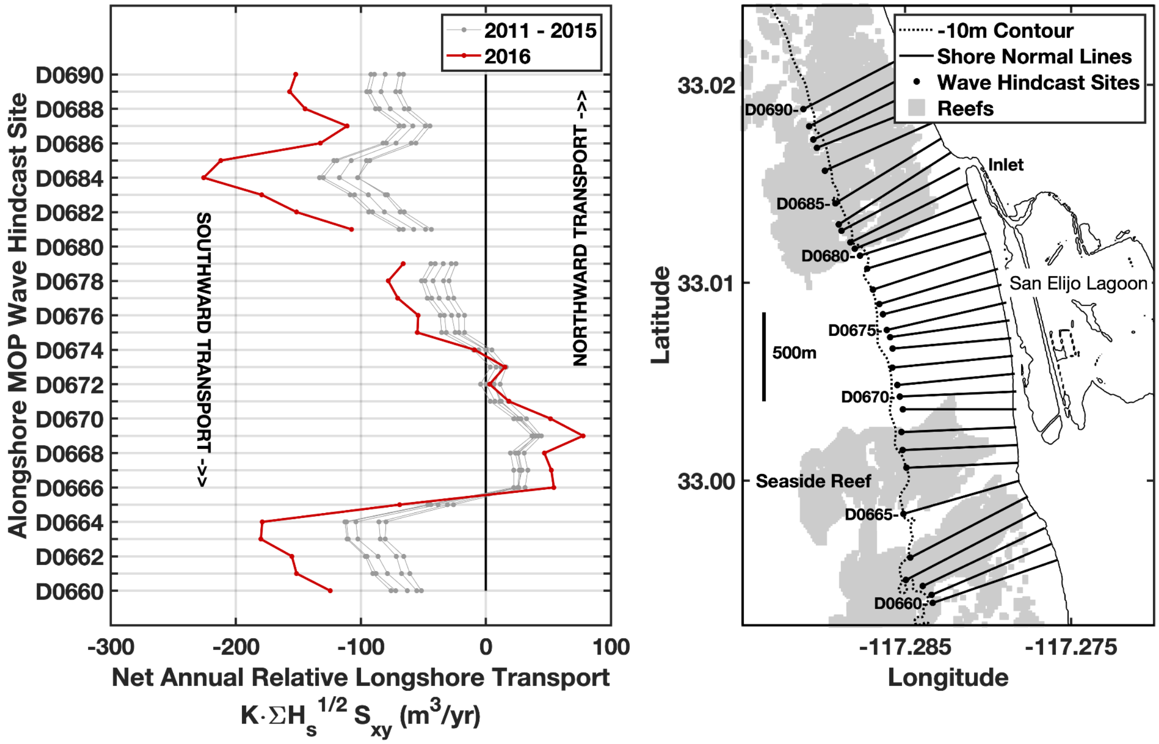

Fig. S2. 2011-2016 wave-driven net annual relative sediment transport for the Cardiff coastline from the CDIP MOP system. In the non-El Niño beach years from 2011-2015 (gray lines, left panel), southward transport slows in front of the lagoon (right panel), with a mild northward (positive) transport reversal near Seaside Reef. During the strong El Niño wave winter in 2016 net southward transport was enhanced significantly (red line). The wave hindcasts are in 10 m depth and not influenced by the shallower portions of the reefs that physically block longshore sand migration (Fig. S1).

Text S2. Observed Beach Changes vs. The Bruun Rule

The Bruun (1962) Rule for MSLR-driven shoreline recession is:

(B.1) $\Delta X_{MSL} = \Delta Z_{SL} \cdot L \,/\, (h+B) = \Delta Z_{SL}/\beta_{AP}$,

where ΔZ_{SL} is sea level rise, L = horizontal length of the "active profile" from the “closure depth” (h) to the berm top height (B). The active profile has height (h+B) and mean slope

$\beta_{AP} = (h+B)\,/\,L$. As sea level rises, L (and β_{AP}) can change depending on the inland profile elevation and erodibility. For the idealized case of both instantly erodible and conveniently β_{AP}-sloped inland geomorphology, L and β_{AP} remain constant with sea level rise and the present active profile shape elevates and shifts inland (Eq B.1).

The Bruun Rule is oversimplified (Cooper and Pilkey, 2004) but is nevertheless widely used. Large sources of uncertainty in applying Eq. B.1 are the true erosion rates of the inland geomorphology (if not sand) and the length L of the hypothetical, conceptual equivalent “active profile”. Alternatively, the Bruun Rule can be used to estimate the volume of added sand needed to "keep pace" or "hold the line" with MSLR (ΔX_{MSL} = 0),

(B.2) $\Delta V_{MSLR} = \Delta Z_{SL} \cdot L = \Delta Z_{SL} \cdot (h+B)/\beta_{AP}$,
where ΔV_{MSLR} has units of m^3/m of shoreline.

Eqs. B.1 and B.2 can be (inversely) used to predict beach widening with added sand volume and constant sea level. That is, the Bruun Rule ratio of beach width to beach volume change,

(B.3) $C_{Bruun} = \Delta X / \Delta V = [\, \Delta Z_{SL} \cdot L / (h+B) \,] / [\, \Delta Z_{SL} \cdot L] = 1 / (h+B)$
where ΔX has units of m and ΔV has units of m^3/m of shoreline. C_{Bruun} depends only on the active profile height (independent of profile slope). A wide range of equivalent closure depths could be used at Cardiff. Here we use a depth range of 8-20 m depth and a berm height of 2 m, yielding C_{Bruun} = 0.045 to 0.10 m of beach width increase for each 1 m^3/m of shoreline of added sand.

Using observations between El Niños from 2010-2015 (ΔX=15 m, ΔV=158K m^3/1,700 m of shoreline, Section 3.2),

(B.4) $C_{Observed} = 0.16$, and the ratio $C_{Observed} / C_{Bruun}$ is between 1.5 and 3.5.

Similarly, the estimated strong El Niño permanent beach narrowing from 2015-2016 (-5.5 m attributed to the net -59K m^3 loss of nearshore sand (Section 3.3) is underpredicted by Bruun (1962) (-1.6 m to -3.5 m). The estimated sand additions required to keep up with sea level rise (Fig. 8) are between 0.3 and 0.6 of a Bruun based estimate (Flick and Ewing, 2009).