LOCAL COASTAL PROGRAM
SEA LEVEL RISE GRANT PROGRAM

LOS ANGELES REGION SHORELINE CHANGE PROJECTIONS

Prepared for
CITY OF SANTA MONICA
Santa Monica, California

Prepared by
TERRACOSTA CONSULTING GROUP, INC.
San Diego, California

Project No. 2391-15
September 30, 2016

TerraCosta Consulting Group

Geotechnical Engineering
Coastal Engineering
Maritime Engineering

Project No. 2391-15
September 30, 2016

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Dear Mr. Wong:

We are pleased to provide the attached report showing results of the subject study. We conducted the study in cooperation with Environmental Science Associates (ESA), the United States Geological Survey (USGS), and the University of Southern California (USC) Sea Grant Program. We modeled coastal change projections to year 2100 relative to 2000 for a range of sea level scenarios consistent with current State of California guidance, and using wave and other information provided by ESA and USGS.

We have forwarded the model results to you as "shapefiles" suitable for viewing in ArcGIS. Please contact us if you have questions, or require additional study products, such as printed output, or any further information.

Respectfully yours,

TerraCosta Consulting Group, Inc.

Reinhard E. Flick, PhD
Principal Oceanographer

Adam P. Young, PhD
Oceanographer

REF/APY/jg
Attachment

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1 INTRODUCTION

This study of the LA Region builds on the results of the *AdaptLA* overview-level work coordinated by the University of Southern California Sea Grant Program (USC Sea Grant 2013) and prepared for the City of Los Angeles Mayor's Office. TerraCosta Consulting Group (TerraCosta) contributed to the *AdaptLA* work by conducting a review of the major coastal geographic regions within the City of Los Angeles. TerraCosta provided an overview of each section's main issues, potential adaptation strategies, constraints, and possible next steps the City could consider in planning for sea level rise (TerraCosta 2013, USC 2013). We summarize the *AdaptLA* results and other historical background as they apply to the Los Angeles Region in Section 4 below.

Section 2 following this introduction reviews the original scope of work and the changes made necessary and agreed to during the course of the project. A summary of results appears in Section 3. Section 4 presents the coastal overview developed during the *AdaptLA* work. Sections 5 and 6 respectively discuss the sea level rise scenarios and the wave data used for the modeling. Section 7 details the short-term wave-driven shoreline fluctuation model and the long-term sea level rise driven coastal retreat model that were used. Section 8 summarizes the modeling results. A discussion of the longshore transport of sand modeling projections is given in Section 9. Finally, several recommendations arising from the technical work are suggested in Section 10.

2 SCOPE OF WORK

The City of Santa Monica was the lead agency for this study. In accordance with the City's request, TerraCosta is herein providing the summary of state-of-the-art shoreline change and coastal retreat modeling from Pt Dume in Malibu, to Malaga Cove in southern Santa Monica Bay (Figure 1). The digital output files of the modeling results have been provided separately. TerraCosta conducted this work in partnership with Environmental Science Associates (ESA) and the United States Geological Survey (USGS) who provided most of

the essential input data, and the University of Southern California (USC) Sea Grant Program, which guided and coordinated the project.

TerraCosta modeled projected coastal change to year 2100 relative to 2000 for a range of mean sea level rise scenarios consistent with the current but evolving State of California guidance. We used wave and other information provided by ESA and USGS, and the model methodologies published by Young *et al.* (2014), Chadwick *et al.* (2011, 2014), and Yates *et al.* (2009). The model output is in the form of "shapefiles" suitable for viewing in ArcGIS.

TerraCosta completed the following tasks:

Task 1. Modeled short-term wave-driven future shoreline position changes.

Task 2. Modeled long-term sea level rise-driven future shoreline changes.

Task 3. Coordinate with USGS (CoSMoS) and ESA-PWA, including determination of suitable mean sea level rise projection scenarios.

Task 4. Participated in public outreach and education support.

Task 5. Participated in the Los Angeles Regional Planning Team.

The tasks completed differed slightly from the work originally proposed due to requests by the City of Santa Monica, unavoidable delays, and other factors that made certain parts of the proposed work impossible or unnecessary. For example, the original proposal specified both historical and projected shoreline fluctuation and coastal cliff retreat modeling limited to Santa Monica Bay from Santa Monica to Redondo Beach. Instead, TerraCosta and the City agreed to extend the projections west to Malibu by forgoing the historical reconstruction, for which insufficient reliable information existed in any case.

3 SUMMARY OF RESULTS

This study was limited to the coastal reach from Pt Dume in Malibu to Malaga Cove in Redondo Beach. This was the extent where input parameters needed to run the coastal retreat model were available. The main findings were:

- Owing to the relatively wide and stable existing beaches, model results suggest that troublesome levels of beach retreat are unlikely to occur before 2050 in and south of Santa Monica, even when the 1.67 m rise by 2100 trajectory is combined with maximum plausible levels of temporary storm erosion.

- In Malibu, model results for both the 0.93 m and 1.67 m sea level rise scenarios suggest that long segments of beach may essentially disappear by 2030 during times of peak tides and high water levels, while cliff retreat will occur simultaneously in areas that remain unarmored.

- By late this century, and assuming the 1.67 m sea level rise scenario, beach retreat will be obvious everywhere in the modelled region. This will lead to economic losses due to reduced beach width for recreation, but also to more frequent and more severe coastal facilities flooding and related damages that will vary by geographic region.

4 COASTAL OVERVIEW

The Los Angeles (LA) Region, comprised of its cities and county, faces numerous planning challenges due to expected climate change impacts. An important element of climate change is sea level rise, which will almost certainly strongly affect the iconic LA coast over the next century and beyond. LA's coast contains extremely valuable private and public property including critical transportation and utility infrastructure and public access, two sewage treatment plants, two power plants, Marina Del Rey and King Harbor small craft harbors, several piers, Los Angeles International Airport, the ports of Los Angeles and Long Beach, and sandy beaches from the Ventura County line through Long Beach.

Sea level rise is the dominant process that will continuously and inexorably exacerbate episodic coastal erosion, flooding, and damages, as most recently demonstrated by Bromirski *et al.* (2016). These problems occur most frequently on the southern California coast when large storm-driven waves coincide with peak high ("King") tides and elevated sea levels related to storm surge and oceanographic effects, including unusually warm coastal waters from El Niño events.

LA encompasses five distinct coastal regions, the first four of which are in Santa Monica Bay: 1) Malibu; 2) Pacific Palisades; 3) Will Rogers State Beach to Redondo Beach; 4) Palos

Verdes, and; 5) San Pedro through LA-Long Beach Harbor. Each region has a unique coastal setting and a different history of development and human intervention. For these reasons, each area has a distinct suite of current and future coastal problems. Similarly, each area likely has dissimilar sensitivity to the effects of future mean sea level rise and so will require different adaptation strategies to remain viable. Detailed descriptions of the LA coast can be found in Orme (2005) and Sherman and Pipkin (2005).

The coast from the Ventura County line to Will Rogers State Beach is south facing with relatively high relief. Sand transport tends to be from west to east. Narrow beaches and heavy development characterizes most of this reach, especially in Malibu east of Pt Dume, with highly valuable residential real estate. However, the reach also features heavily used state and county beaches, such as Zuma State Beach. Pacific Coast Hwy (PCH) through Malibu and Pacific Palisades is the essential coastal transportation and utility corridor as the only alternate route to Fwy 101 located north of the coast mountain range. Much of eastern Malibu and most of the reach from Topanga Canyon to Will Rogers State Beach consists of narrow packet beaches mostly backed by various shore protection revetments protecting the coast highway. The extent of existing revetments shows that this reach has and continues to experience episodic erosion that threatens to undermine PCH.

The coast turns southward at Will Rogers State Beach, which is moderately wide owing to its successful and relatively unobtrusive groin beach stabilization system. Toward the southeast, beach width increases due to the up-coast influence of the Santa Monica breakwater located just offshore of Santa Monica pier. The breakwater, built in the 1930s as an unsuccessful attempt to create a small craft harbor, did lead to an astonishing increase in beach width and equally important, to beach width stability.

The reach from Santa Monica to Redondo Beach provides major economic benefits from coastal recreation and tourism, boating, and utility and facility siting. These beaches are wide to very wide (relative to the southern California norm), and largely created by sand supplied as by-products of coastal construction, including LAX, Marina Del Rey, and the Hyperion sewage treatment plant (Flick, 1993; Leidersdorf and Woodell, 1993, 1994). Between the late 1930s and 1963, over 24 million cubic meters (m^3) of sand were placed.

While these southern Santa Monica Bay beaches have been wide and stable for many decades, gradual retreat is in progress. A major concern for the future arises from the fact that

opportunistic sand is unlikely to be available in the quantities it was up to the 1960s. As MSLR accelerates in the future, these iconic LA beaches will undoubtedly narrow at a faster rate, as demonstrated by the model results presented herein. However, it is unlikely that sea level rise alone will appreciably exacerbate storm-wave driven erosion, flooding, or property damage in the near future, meaning several decades. But if MSLR takes one of the higher trajectories, these problems are likely worsen starting about mid-century.

The Palos Verdes Peninsula section of LA has a long history of geological instability (Griggs *et al*. 2005). The south-facing peninsula is exposed to the ocean, while the east-facing section is sheltered behind the LA-Long Beach outer breakwater, which has its root at Cabrillo Point. Both sections are heavily sub-urbanized atop a flat coastal terrace that has a 35 m high sea cliff at its seaward edge. The geology suggests relatively resistant formations at sea level near Cabrillo Point, but more erodible material to the west toward Point Fermin. As MSLR resumes and accelerates, the weaker western cliff sections will be subject to more undermining from wave action and eventual collapse than the more resistant eastern sections.

5 SEA LEVEL RISE SCENARIOS

TerraCosta with the other team members carefully considered the selection of the sea level rise scenarios used for modeling. By mutual agreement with the City of Santa Monica we settled on the California Coastal Commission sea level rise policy guidance (CCC 2015) “projection” and “high” trajectories, supplemented with an “extreme” scenario from Cayan *et al*. (2016). We herein refer to these three trajectories by their 2100 end-point values to avoid confusion among qualitative descriptors like “high” since these are evolving and have will frequently changing end-points.

Figure 2 shows the two trajectories (green and black) with respective 2100 end-points of 0.93 m (about 3 ft) and 1.67 m (5.5 ft) used for the coastal change modeling, and the third (red) trajectory with 2.88 m (9.4 ft) rise by 2100 presented for discussion purposes. Table 2 summarizes the 2030, 2050, and 2100 sea level rise values (relative to 2000) for these trajectories, further described below. Note that approximately 1.67 m of sea level rise is occurs in the 2.88 m scenario by about 2080 (Figure 2). This means that the shoreline retreat for this projection would be about equal to that for the 1.67 m scenario, but occur about 20 years earlier.

The CCC (2015) guidance is based on the National Research Council report (NRC 2012) prepared for California, Oregon, and Washington. The guidance contains three scenarios then recommended for consideration in coastal planning. These included the 0.93 m and 1.67 m trajectories considered herein, and 0.42 m, which was not used because revisions currently underway in California sea level rise policy due in 2018 will very likely eliminate it.[1] An interesting feature of the 2.88 m scenario is that it lies between the 0.93 and 1.67 trajectories until about 2055 when polar ice melt is expected to dominate sea level rise for this scenario (Figure 2).

Table 2. Summary of Projected Sea Level (see Figure 2)

Year	Sea Level Rise Relative to 2000 (meters)		
	0.930 m (3 ft, green)	1.67 m (5.5 ft, black)	2.88 m (9.4 ft, red)
2030	0.150	0.300	0.178
2050	0.290	0.610	0.519
2100	0.930	1.67	2.88

The 2.88 m scenario is derived from the currently evolving State of California sea level rise policy guidance founded on important advances in sea level rise science that have occurred since early 2016. Cayan *et al*. (2016), working in support of the 2018 Fourth Californian Climate Change Assessment, cite DeConto and Pollard (2016) who suggest ice sheet melting in Antarctica will be greater than previously expected. In addition, Kopp *et al.* (2014) have developed a probabilistic approach that assigns likelihoods to various future mean sea level rise scenarios.

Their (current) extreme projection is the 99.9%tile trajectory of the IPCC (2008) RCP 8.5 scenario as tabulated in Cayan *et al.* (2016). This "business as usual" greenhouse gas build up would produce an 8.5 Watt/m^2 radiative imbalance by 2100,[2] with an associated mean sea level rise of 2.88 m. This means, from what we can best estimate now, there is 1 chance in

[1] In effect, the former medium and high trajectories have become the new low and medium ones, with a new high, now termed "extreme." This illustrates the confusion these descriptors can promote.

[2] For reference, earth's current imbalance is about 0.8 Watt/m^2.

1,000 (0.1%) that this extreme scenario will be reached or exceeded, and 999 chances in 1,000 that sea level rise will follow a lower trajectory.

We did not model the shore change associated with this new extreme sea level rise scenario for two reasons. First, the changes that are looming in the state guidance began to appear while the model production runs were nearly complete. While we proposed to model all three CCC (2015) scenarios, the study partners determined that it would be more advantageous to model the 0.93 m and 1.57 m scenarios only, and spend the time saved considering the evolution of the science and guidance. There are several other aspects to this. First, the extreme scenario of 2.88 m sea level rise by 2100 is currently deemed extremely unlikely, as already mentioned. Second, this trajectory is not currently State of California guidance since the pending updates will not be available until 2018, and could change in the meantime.

Finally, the Young *et al.* (2014) coastal retreat model assumes that backshore (usually cliff) erosion can proceed rapidly enough to provide sufficient sand to maintain the "equilibrium" beach shape, which rises and moves landward in response to sea level rise (Bruun 1962). While we did not make a quantitative assessment of the model limits, we recognize that for sufficiently high sea level rise rates some cliffs may not be able to erode fast enough to keep up with the sand supply needed. In such a case, the beach would eventually disappear as the shoreline retreats faster than the cliff can retreat. This is also the situation where sea walls back a retreating beach, and at many headlands, which are usually composed of harder rock at sea level than the surrounding coast, and where wide sandy beaches do not form for this reason.

6 WAVE INPUT DATA

USGS provided modeled hindcast (1980-2011) and forecast (2012-2100) wave parameters at nearshore virtual buoys in approximately 10 m water depth (MOP locations, Figure 1) at three-hour time intervals. The draft Coast of California Storm and Tidal Waves Study (CCSTWS) for the LA region (USACE 2010) provided estimated closure depths at 23 locations in the study area used for the modeling. Closure depth is the depth seaward of which no wave-driven sand transport occurs. It is a critical element of the Young *et al.* (2014) model, as explained Section 7.2 below.

7 COASTAL CHANGE MODELING

We used the wave projections and the equilibrium shoreline change model of Yates *et al*. (2009) to estimate the short-term (three-hourly to seasonal) shoreline position fluctuations at each MOP transect line in the study area from 2012-2100. We used the sea level rise scenarios and the Young *et al.* (2014) model to project longer-term (annual-century) coastal retreat, also at each MOP line, from 2000-2100.

Results for the two scales of temporal variation were added together to provide time series of coastal change at the approximately 100-meter transect intervals. The model was applied to about 600 MOP transects (numbered 2900 to 2300) over the 60-km reach from Pt Dume to Malaga Cove (Figure 1) where model input information was available. Some gaps in model inputs such as beach change coefficients precluded full modeling at all MOP transects.

The following list contains the inputs and modeling and mapping methods and assumptions applied in our approach, and which are presented in more detail in the following sections.

1. Primary Model Inputs
   - USGS wave data
   - USGS bare earth digital elevation model (DEM)
   - USGS beach change coefficients
   - ESA transect profiles (extended offshore)
   - CCC (2015) 0.93 m and 1.67 m sea level rise trajectories
   - USACE (2010) – CCSTWS LA (Draft Report) closure depths
   - Back shore sand content measured from over 70 samples

2. Modeling Methods and Assumptions
   - Model independent of historical erosion rates
   - Future shoreline profile transgression based on equilibrium sand balance from peer-reviewed model (Young *et al.* 2014)
   - Wave-driven beach fluctuations from peer reviewed model (Yates *et al.* 2009)
   - Beach and cliff retreat conditionally decoupled permitting different retreat rates
   - Short-term beach changes projected every three-hours
   - Long-term shoreline retreat projected annually

3. Mapping Methods and Assumptions
   - Model projections at 100-m spaced transects
   - No smoothing applied
   - Retreat results should be interpreted broadly
   - Shorelines clipped at locations where adjacent transects were not modeled (*e.g.*, inlets, transects with infrastructure covering the cliff base/top, etc.)
   - Backshore erosion is initiated when waves reach backshore
   - Armoring not considered in modeling
   - Armored locations are delineated

7.1 Wave-Driven Fluctuations

Yates *et al*. (2009) developed and tested an equilibrium short-term shoreline position model to calculate wave-driven beach fluctuations consisting of both accretion and erosion, depending on wave conditions. Modeling time step is limited only by the frequency of available wave information, in this case every three hours. The model does not account for backshore features such as cliffs or seawalls that can inhibit horizontal erosion, or for bedrock platforms that prevent vertical erosion. In addition, sand budget shortages or surpluses are also not considered, but these can be added *ad-hoc* (Chadwick *et al*. 2014).

The Yates *et al.* (2009) model requires four empirically derived constants for each modeled section of beach. These are denoted a, b, C^+, and C^-, as described in the model governing Equations 1 and 2 below. USGS derived the constants by analyzing beach change data and wave observations and provided them to TerraCosta. The constants were only available for the TerraCosta study area (MOP transects 2900-2300) shown in Figure 1, which limited our modeling to this reach of the LA coast.

Equation 1 expresses the model assumption that for a given wave energy, E_{eq} there exists an "equilibrium" shoreline position S that is constant as long as the waves do not change, and that this position is linearly related to the wave energy through the constants a and b:

$$E_{eq} = aS + b \qquad (1)$$

The model also assumes that the time rate of shoreline change, dS/dt depends on the instantaneous wave energy, E, and energy dis-equilibrium, ΔE (see Footnote[3]):

$$dS/dt = C^{\pm} E^{1/2} \Delta E, \qquad (2)$$

where $\Delta E = E - E_{eq}(S)$, and $C^{\pm}$ are change rate coefficients for accretion (C^{+} when $\Delta E<0$), and erosion (C^{-} when $\Delta E>0$).

The wave-driven beach change model results are available every three hours for the modeled time interval from 2012 to 2100. Figure 3 shows an example of the nearly 100-year long time series of model input wave height and output shoreline position for MOP location 2500 at El Segundo. Maximum wave heights range up to about 3.5 m, while corresponding shoreline retreat reaches 35-40 m. Varying durations of high waves that are not apparent at this time resolution account for larger or smaller shoreline retreat for apparently similar storm wave heights.

Comparable time series of shoreline fluctuations at each transect make possible the calculation of erosion return period statistics at each of the 600 MOP lines, including maximum projected erosion values. Figure 4 shows the 1% (100-year) recurrence and maximum values of storm-driven beach erosion for the study area. The model suggests erosion "hot spots" in the central part of Santa Monica Bay (MOP lines 2550-2480), south of Marina del Rey into Manhattan Beach. Storm erosion magnitude decreases north of Marina del Rey (MOP 2540), but shows a few more hot spots (MOP 2780, 2910) in Malibu.

7.2 Sea Level Rise Driven Coastal Retreat

The "conditionally decoupled profile model" of Young *et al.* (2014) was employed to project the longer-term (annual and longer) sea level rise driven coastal retreat. This model uses a sand balance approach based on Bruun (1962) to derive retreat as a function of sea level rise. The crucial assumption underlying the Bruun model is that as sea level rises, the geometric relationship between the beach profile and sea level remains constant, all other variables (*i.e.* wave climate, sand grain size, and sand availability) being equal. In other words, as sea level goes up, the beach cross section moves upward at the same rate, but also migrates landward eroding the upland at a rate sufficient to provide just enough sand to maintain the shifting

[3] $E = H^2/16$, where H is wave height (density of water and acceleration of gravity are neglected).

profile. The idea is that beaches look essentially the same relative to sea level no matter what the actual sea level.

Over long time scales, centuries to millennia, this is a reasonable assumption. A crucial improvement made by Young *et al.* (2014) is using actual coastal topography. This advance was possible first by increased computer power, and second by the availability of accurate digital coastal elevation models and reasonably reliable beach cross section profiles. Over shorter timescales such as years to decades, the model also assumes that the upland can erode fast enough and contains sufficient sand to maintain the profile. This criterion is readily met in the case of wide beaches, where sand from the upper profile moves offshore to raise the lower portion of the profile as sea level rises. For narrow beaches backed by sea cliffs, such as those in Malibu, we also considered the percentage of beach size sand in the cliffs.

TerraCosta determined cliff height from the digital elevation model used in the analysis, as shown in Figure 5. We also collected and analyzed sand samples for grain size at 78 cliff and backshore locations throughout the study area. These samples were wet sieved using a 63-micron sieve to determine the percent of backshore sand content available for beach sand balance. Values ranged from 23-100 % with an average of 74%. The highly irregular cliff sand content was smoothed alongshore, as shown in Figure 6.

For each annual time step, the active beach profile (defined as extending from the offshore closure depth to the upper active beach limit) shifts vertically by the amount of projected sea level rise, and the sand needed to accommodate the shift is calculated. As long as the upper beach is sufficiently wide to provide the needed sand, the beach is “decoupled” from the upland, *i.e.*, the cliff, and marine erosion does not affected it. Sea cliffs still provide some sand, however, from subaerial erosion, especially rainfall. Marine-driven cliff erosion occurs when the beach retreats landward sufficiently for the active profile to reach the cliff.

Decoupling the active beach and cliff profiles in the Young *et al.* (2014) model allows the beach and cliff to conditionally retreat at different rates. Typical profile adjustments show that the initial beach landward shifts can obtain sand balance without marine-driven cliff erosion. When the beach buffer width vanishes, waves begin to erode the cliff base and (ignoring possible lag time) the active beach and cliff profile become coupled, retreating at the same rate.

TerraCosta ran the model to project shoreline change from 2000 to 2100 on transects spaced 100 m alongshore. Transects were initially provided by USGS at MOP locations, then edited and reoriented by ESA, and lastly extended farther offshore by TerraCosta. Final transect orientation generally increased from north to south (Figure 7), following the overall coastal trend. North and west of Will Rogers State Beach (around MOP 2650) the prevalence of headlands complicates the coastal orientation.

Topographic and bathymetric profiles were obtained at each transect using a 1-m resolution bare earth digital elevation model provided by USGS. Cliff base and cliff top locations at each transect were initially defined by ESA and edited by TerraCosta. Transect closure depths were interpolated from 23 modeled values in the study area (USACE 2010) and the upper active beach limit was estimated from rectified aerial imagery. Unrepresentative transects and transects with structures covering cliff top and/or base were removed from the analysis. Armoring and seawalls locations were mapped by updating and editing the Coastal Commission armoring shapefile (developed by Jennifer Dare) using more recent oblique and vertical aerial imagery.

Transects that intersected the armoring shapefile were identified and modeled assuming no armoring was present. This should not be taken to suggest that the armoring would or would not fail, or whether and when it would be overtopped. Each section of armored coast would have to be examined in detail by engineers on the ground to make these determinations, which are outside the scope of this study.

8 COASTAL CHANGE PROJECTIONS

TerraCosta computed projected wave-driven beach fluctuations and sea-level driven beach and cliff retreat from 2000-2100 using the methods described respectively in Sections 7.1 and 7.2 above. This section presents statistical summaries of the results and one example map of the projected shoreline positions at Santa Monica for the years 2030, 2050, and 2100.

Figures 8 summarizes the shoreline retreat for beaches in the study area under the two sea level rise trajectories described in Section 5 (endpoints of 0.93 m and 1.67 m) for years 2030, 2050, and 2100 relative to 2000. Long-term retreat ranges from about 5 m, 20 m, and 50 m respectively in the three target years for the 0.93 m sea level rise scenario, and 10 m, 30 m, and 90 m respectively for the 1.67 m scenario. Projected beach retreat is largest for both scenarios in the southern part of the study area, peaking at about MOP 2450 near El Segundo

just south of Marina Del Rey. Note that there is large variability in retreat for the 1.67 m scenario by 2100, especially in this southern reach. The reasons for this are not entirely clear, but may provide an estimate of modeling uncertainty.

Figure 9 includes both the long-term beach retreat from sea level rise (for both scenarios) from Figure 8, with the added maximum wave-driven shoreline erosion shown in Figure 4. Coincidentally, the maximum short-term erosion of about 50-65 m also occurs between MOP 2400 and 2500, as mentioned in Section 7.1. When combined, the maximum beach retreat during storm episodes reaches about 90 m and 125 m respectively for the 0.93 m and 1.67 m scenarios.

Figure 10 presents analogous results for the long-term retreat of sea cliffs in the areas with little or no beach. These are mainly in Malibu, north of Will Rogers State Beach, and at the very southern end of the study area in Redondo Beach south of King Harbor. Hapke and Reid (2007) compiled historical erosion rates along the California coast, including on 585 ranges in the LA area. These range from zero to about 1.8 m/yr, with an average rate of nearly 0.4 m/yr. Our results find year-to-year cliff retreat rates of 0-0.8 m/yr. These are within the range of the historical cliff retreat rates suggesting that the region's unarmored cliffs can in fact erode sufficiently fast to continue to provide sand to the local beaches.

Figure 11 is an example of the high-resolution shoreline retreat maps resulting from the TerraCosta modeling transmitted to the City of Santa Monic electronically. The non-profit organization *Trust for Public Land* is providing electronic access to these maps, along with other work products from this project and related material from many other sources.[4]

It is clear from Figure 11 that troublesome levels of beach retreat are unlikely to occur before 2050, at least in Santa Monica, even when the 1.67 m trajectory is combined with maximum plausible levels of temporary storm erosion. Nevertheless, by late this century, beach retreat will be noticeable. This may lead to economic losses due to reduced beach width for recreation, but also to occasional coastal facilities flooding and related damages.

Figure 12 is a similar example, but for the much narrower beaches at Malibu east of Pt Dume. In this case, projections for the 1.67 m scenario suggest that long segments of beach

[4] Trust for Public Lands, Climate Smart Cities, Los Angeles website **http://web.tplgis.org/losangeles_csc/**.

will essentially disappear by 2030 during times of peak tides and high water levels, while cliff retreat will occur simultaneously, at least in areas not armored.

If sea level rise actually follows a trajectory such as the 2.88 m by 2100 scenario, then these effects would occur much sooner, as already mentioned. This provides an alternate way to view future projected shoreline retreat: Namely not as a function of sea level trajectory over time, but as shoreline retreat as a function of sea level rise regardless of when it is reached. In other words, the projected shoreline position results shown are valid for the specified levels of sea level rise, subject to the underlying assumptions. In Figure 11, the modeled retreat lines shown for the (2030) 0.300 m, (2050) 0.610 m, and (2100) 1.67 m sea level rise increases are the same no matter when those levels are actually reached.

9 PROJECTED ALONGSHORE SAND TRANSPORT

The former US Army Coastal Engineering Research Center "CERC" equation was used to model projected longshore sand transport (Q_l) at three-hour time steps from 2012-2100 with USGS forecast wave data and parameters (Tp, Dp, Hs, MOP depth). Analysis was conducted on TerraCosta/ESA transect locations using the closest available MOP location. Transect orientation was computed as degrees from North (Figure 6). The breaker wave height (Hb) was solved for iteratively.

$$Q_l = K \frac{\rho g^{0.5}}{16k^{0.5}(\rho_s - \rho)\,(1-n)} H_b^{\frac{5}{2}} \sin(2\,\alpha b) \quad \text{where,}$$

k = breaker index (assumed 0.78)

K = 0.39 (dimensionless coefficient)

ρ_s = density of sediment

ρ = density of seawater

n = pore space factor (assumed 0.4)

g = gravitational constant

Hb = breaker wave height

α_b = breaker wave angle relative to beach

Figure 13 shows a typical time series of the modeled longshore sand transport. In the northern part of the study area, the direction of mean longshore transport rates was scattered but generally northward (Figure 14). In the southern part of the study area the direction was consistently southward. The shape of the Santa Monica Bight and shoreline orientation with respect to the prevailing waves cause the differences in longshore transport direction. Scattered longshore rates in the northern study area resulted from local headlands and points that irregularly alter the breaking wave direction. The center of the study area shows little net transport. Actual longshore transport in the study area is significantly affected by harbors and groins and not modeled here.

10 RECOMMENDATIONS

1. Continue to lead and promote local, regional, state, and federal efforts to monitor and model beach conditions.

2. Monitor all LA Region beaches at least annually in the fall, or more frequently if possible, to provide data to establish the reliability of beach change models and to improve these models, which are needed for projections of future conditions.

3. Facilitate continued delivery of any opportunistic sand supplies that become available for area beaches.

4. Document times, locations, and extent of overtopping, flooding, and erosion undermining of important regional infrastructure, including Pacific Coast Highway, to aid in planning future geotechnical and engineering adaptations.

5. Document times, locations, and extent of cliff failures and other erosion events to aid in developing and planning geotechnical adaptations.

LIMITATIONS

Coastal engineering and science, especially projections of possible future conditions, are characterized by uncertainty. Model results and the related professional judgments presented herein are based on our scientific research experience, our understanding of the Los Angeles area coast, and on evaluation of the technical information and data gathered and produced. Our technical work meets current professional standards. However, we do not guarantee the accuracy or applicability of the modeled shoreline change projections in any respect.

ACKNOWLEDGEMENTS

We gratefully acknowledge the interest and support of the City of Santa Monica, especially Garrett Wong. We appreciate the efforts of our colleagues Matt Brennan, James Jackson, and Bob Battalio at ESA, David Revell of ESA and Revell Coastal, and Patrick Barnard, Li Erickson, and Andrea O'Neill of USGS who provided most of the input data used in this work, and the participation, guidance, and coordination offered by Nick Sadrpour, Alyssa Newton Mann, Phyllis Grifman, and Juliette Finzi Hart of USC Sea Grant. We could not have undertaken or completed this study without their help.

REFERENCES

Bromirski, P.D., R.E. Flick, and A.J. Miller, 2016. Storm Surge Along the Pacific Coast of North America, J. Geophys. Res., Oceans, 121(11).

Bruun, P., 1962. Sea level rise as cause of shore erosion, *J. Waterways Harbors Div*., Amer. Soc. Civil Eng., 88, 117-130.

Cayan, D.R., J. Kalinsky, S. Iacobellis, and D. Pierce, (with R. Kopp), 2016. *Creating Probabilistic Sea Level Rise Projections*, Unpublished White Paper, Division of Climate, Atmospheric Sciences, and Physical Oceanography, Scripps Institution of Oceanography, La Jolla, CA, 16 pp.

Chadwick, D.B, R. Flick, J. Helly, T. Nishikawa, P.F. Wang, W. O'Reilly, R. Guza, P. Bromirski, A. Young, W. Crampton, B. Wild, and I. Canner, 2011. A Framework for Sea Level Rise Vulnerability Assessment for Southwest U.S. Military Installations, *Proc. Oceans 11*, Mar. Tech. Soc., Inst. Electrical and Electronic Eng., 110426-001.

Chadwick, D.B., P.F. Wang, M. Brand, R.E. Flick, A.P. Young, W.C. O'Reilly, P.D. Bromirski, W.A. Crampton, R.T. Guza, J.J. Helly, T. Nishikawa, S. Boyce, M. Landon, M. Martinez, I. Canner, and B. Leslie, 2014. *A Methodology for Assessing the Impact of Sea Level Rise on Representative Military Installations in the Southwestern United States (RC-1703)*, Final Report, submitted to The Strategic Environmental Research and Development Program, Alexandria, VA, 688 pp. http://www.serdp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Climate-Change/Vulnerability-and-Impact-Assessment/RC-1703.

California Coastal Commission (CCC), 2015. *California Coastal Commission Sea Level Rise Policy Guidance: Interpretive Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits, 293* pp. http://www.coastal.ca.gov/climate/slrguidance.html.

DeConto and Pollard, 2016. Contribution of Antarctica to past and future sea-level rise, *Nature* 531, 591-597.

Flick, R.E., 1993. The Myth and Reality of Southern California Beaches, *Shore & Beach*, 61(3).

Griggs, G., K. Patsch, and L. Savoy, 2005. *Living With the Changing California Coast*, University of California Press, 540 pp.

Hapke, C.J. and D. Reid, 2007. *National Assessment of Shoreline Change, Part 4: Historical Coastal Cliff Retreat along the CA Coast,* USGS Report 2007-1133.

Intergovernmental Panel on Climate Change (IPCC), 2008. *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Technical Summary, ("Moss Report") Intergovernmental Panel on Climate Change, Geneva, 25 pp.

Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, *Earths Future*, 2, 383-406.

Leidersdorf, C.B. and G. Woodell, 1994. Human Intervention with the Beaches of Santa Monica Bay, California, *Shore & Beach*, 62(3).

Leidersdorf, C.B. and G. Woodell, 1993. Beach Enhancement through Nourishment and Compartmentalization: The Recent History of Santa Monica Bay, *Beach Nourishment Engineering and Management Considerations, Proc. Coastal Zone '93*, Amer. Soc. Civil Eng., New York, NY.

National Research Council (NRC), 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future,* National Academy Press, Washington D.C., 201 pp.

TerraCosta Consulting Group, 2013. *City of Los Angles Coastal Issues Related to Future Mean Sea Level Rise*, Report prepared for Mayor's Office – City of Los Angeles, 14 pp.

United States Army Corps of Engineers (USACE), 2010. *Coast of California Storm and Tidal Waves Study,* Draft Report, USACE Los Angeles District.

University of Southern California (USC) Sea Grant Program, 2013. *Sea Level Rise Vulnerability Study for the City of Los Angeles*, Report prepared for the Mayor of Los Angeles, 85 pp.

Yates, M.L., R.T. Guza, and W.C. O'Reilly, 2009. Equilibrium shoreline response: Observations and modeling, *J. Geophys. Res. C*, 114, C0910.

Young, A.P., R.E. Flick, W.C. O'Reilly, D.B. Chadwick, R.T. Guza, W.C. Crampton, and J.J. Helly, 2014. Estimating cliff retreat in southern California considering sea level rise using a sand balance approach, *Mar. Geology*, 348, 15-2.

FIGURES

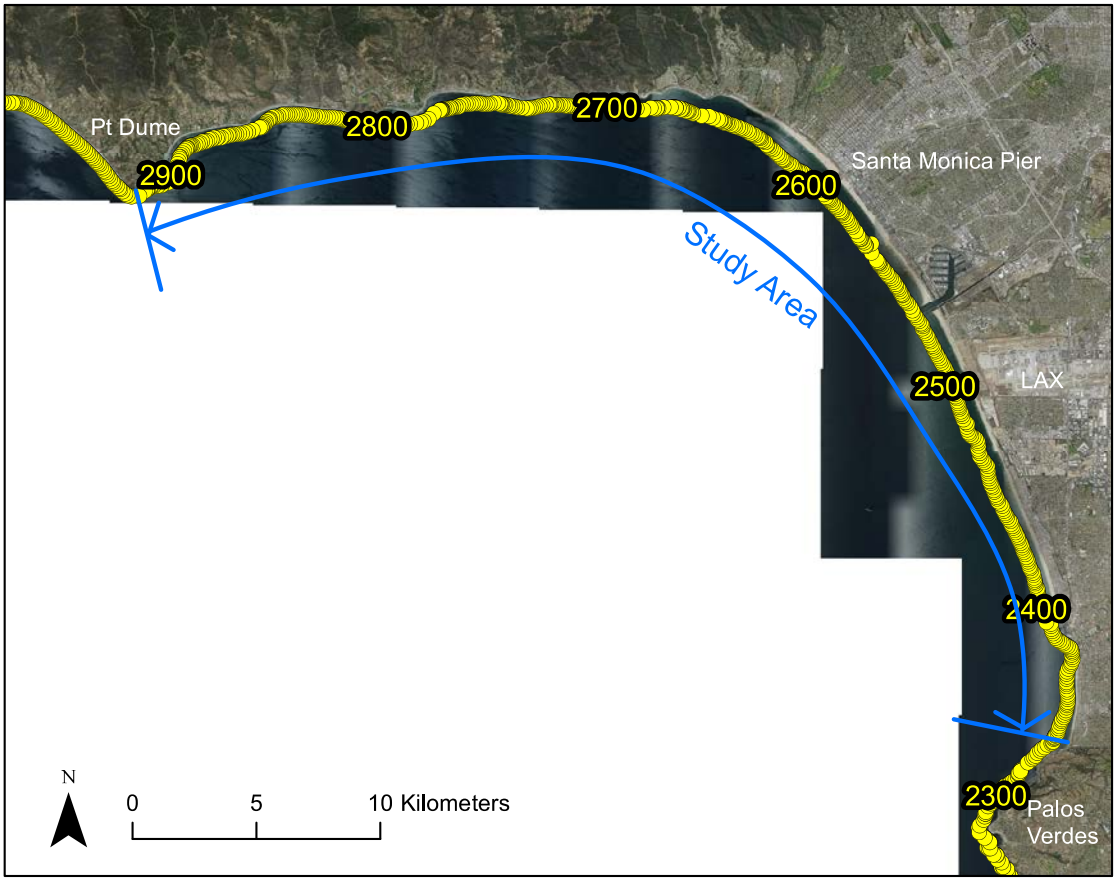

Figure 1. Los Angeles region TerraCosta study area with MOP transects locations.

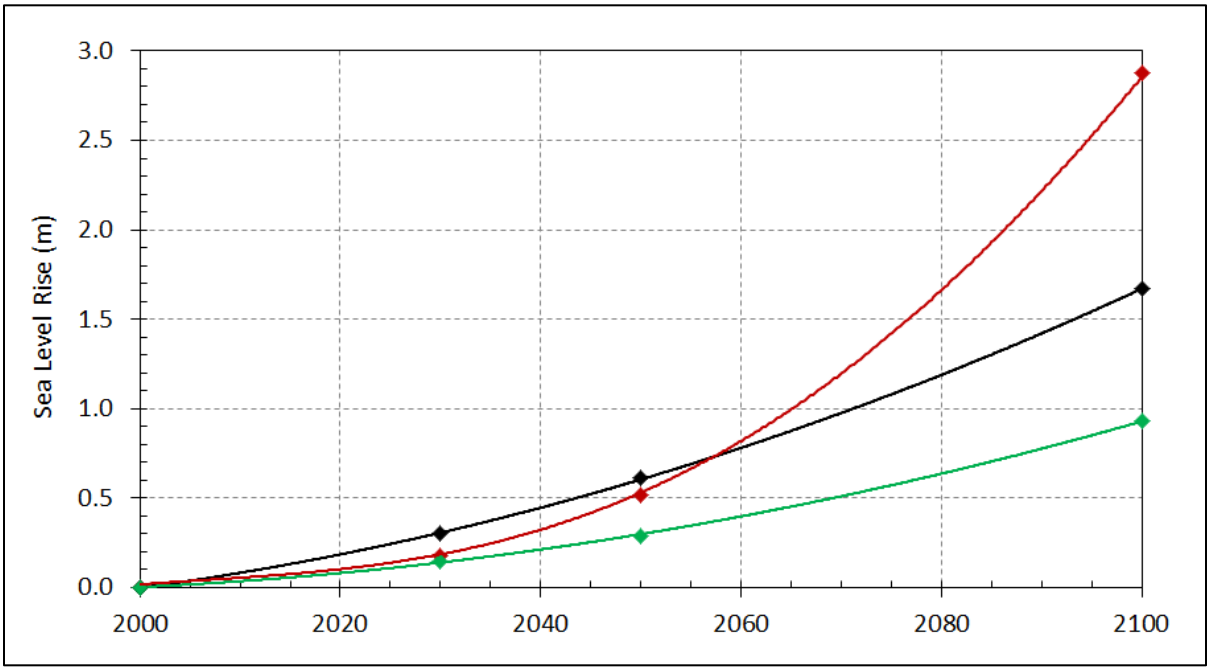

Figure 2. Sea level rise scenario projections (green, black) used in the coastal change modeling and (red) used only for discussion purposes (see text).

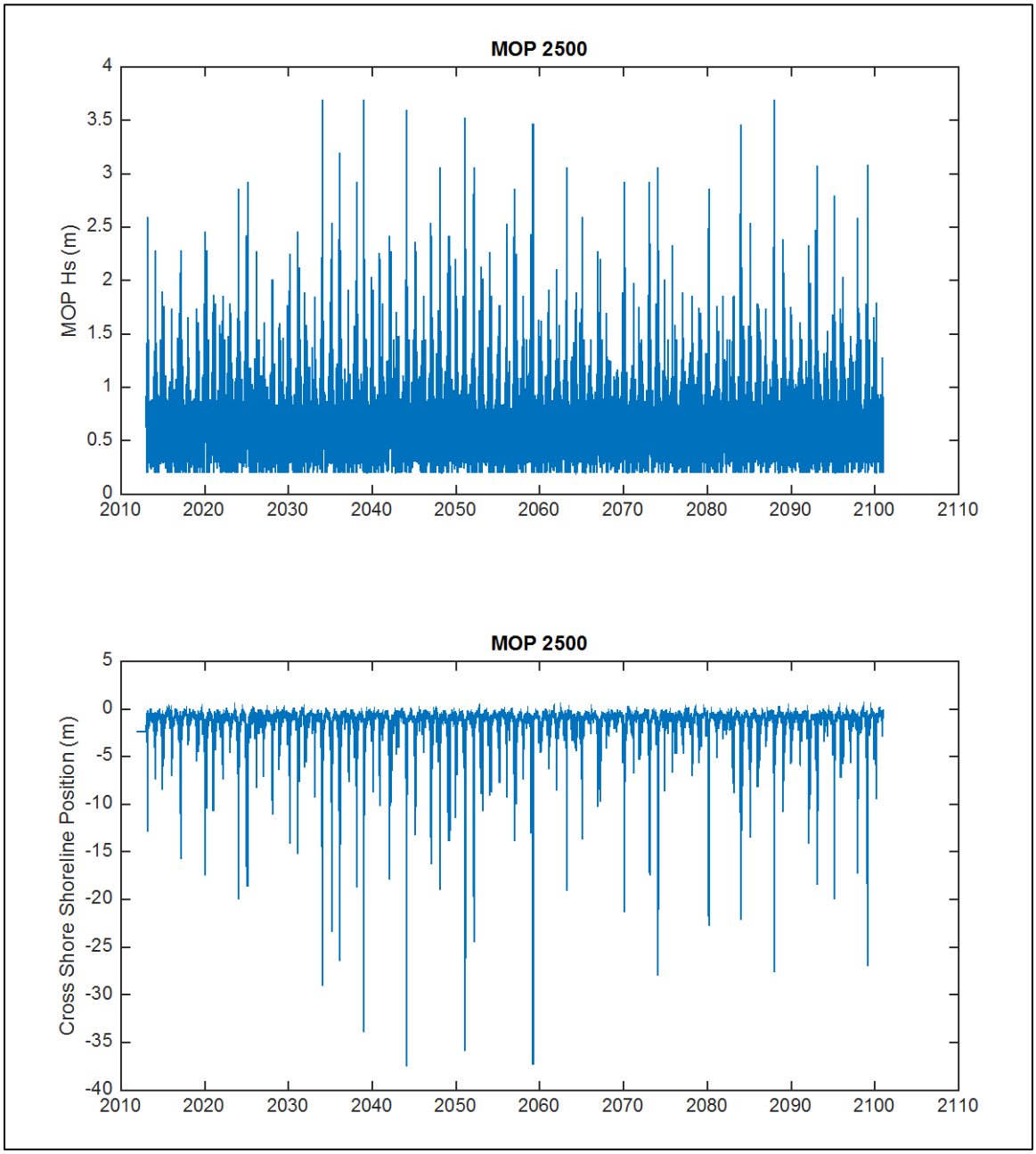

Figure 3. Example time series of wave height (upper) and shoreline fluctuation (lower) from Yates *et al.* (2009) model at MOP 2500.

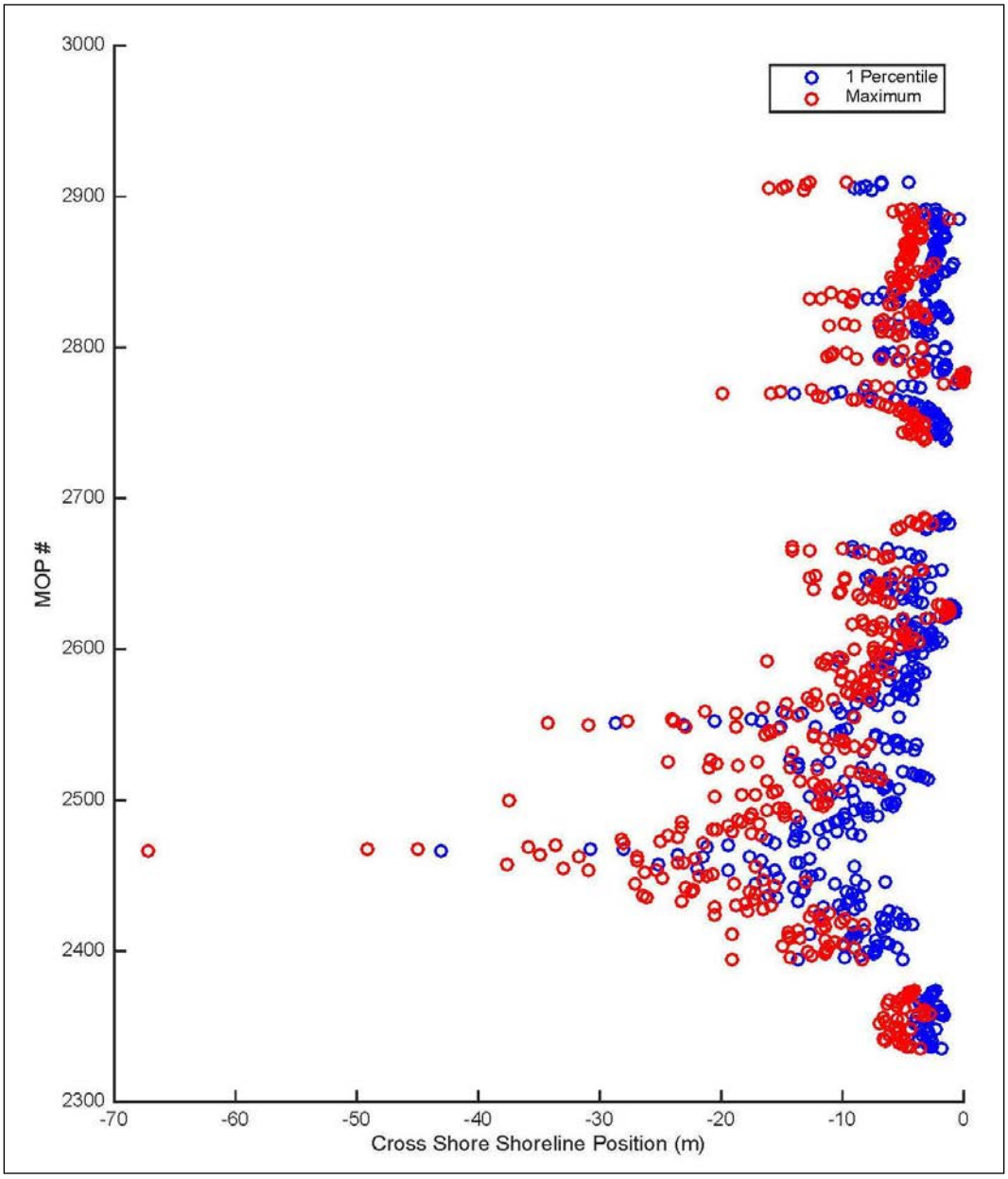

Figure 4. Wave-driven shoreline erosion for the 1%tile (100-year) return period (blue), and maximum (red) events as a function of location (MOP transect).

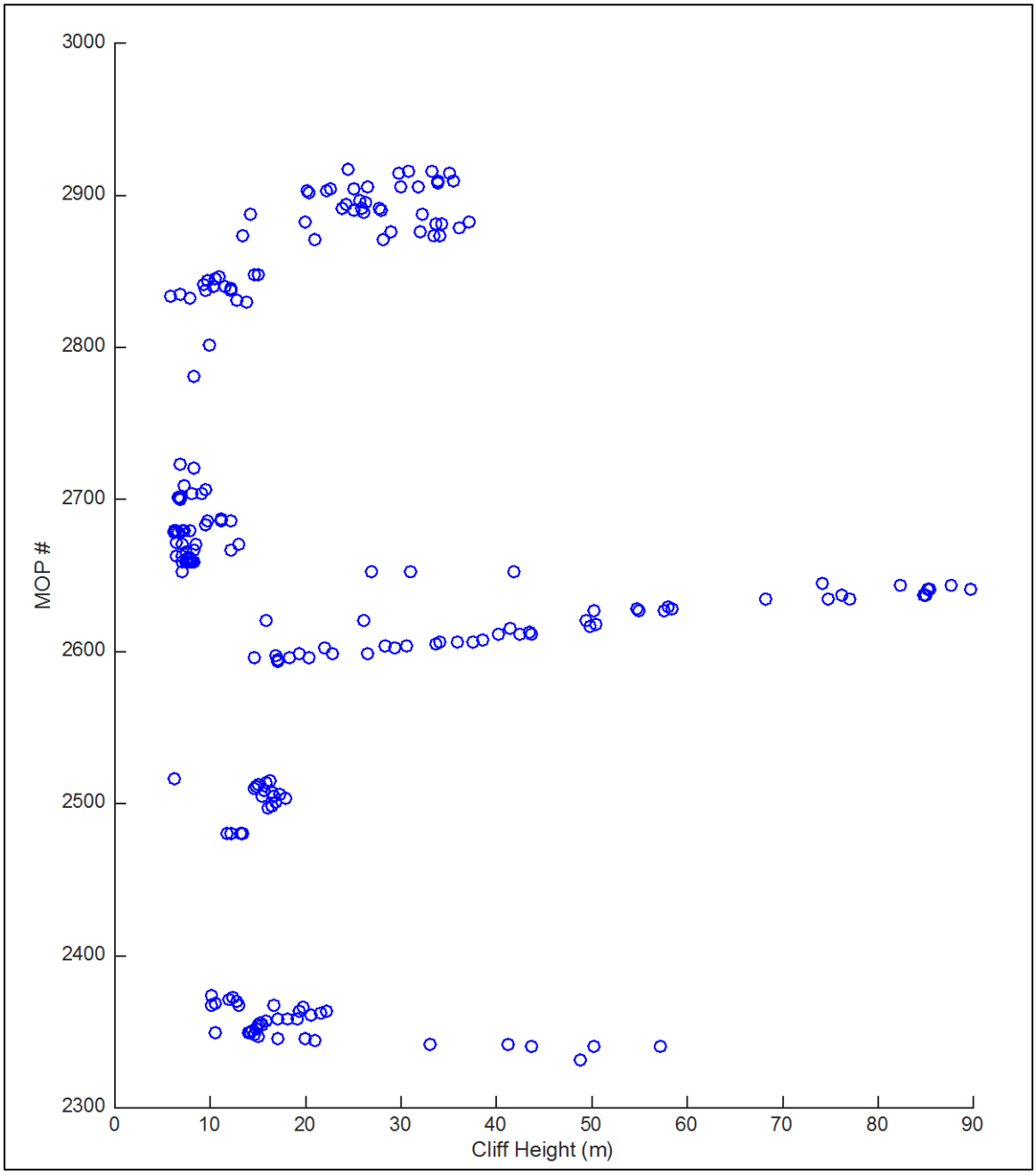

Figure 5. Cliff height as a function of location (MOP transect).

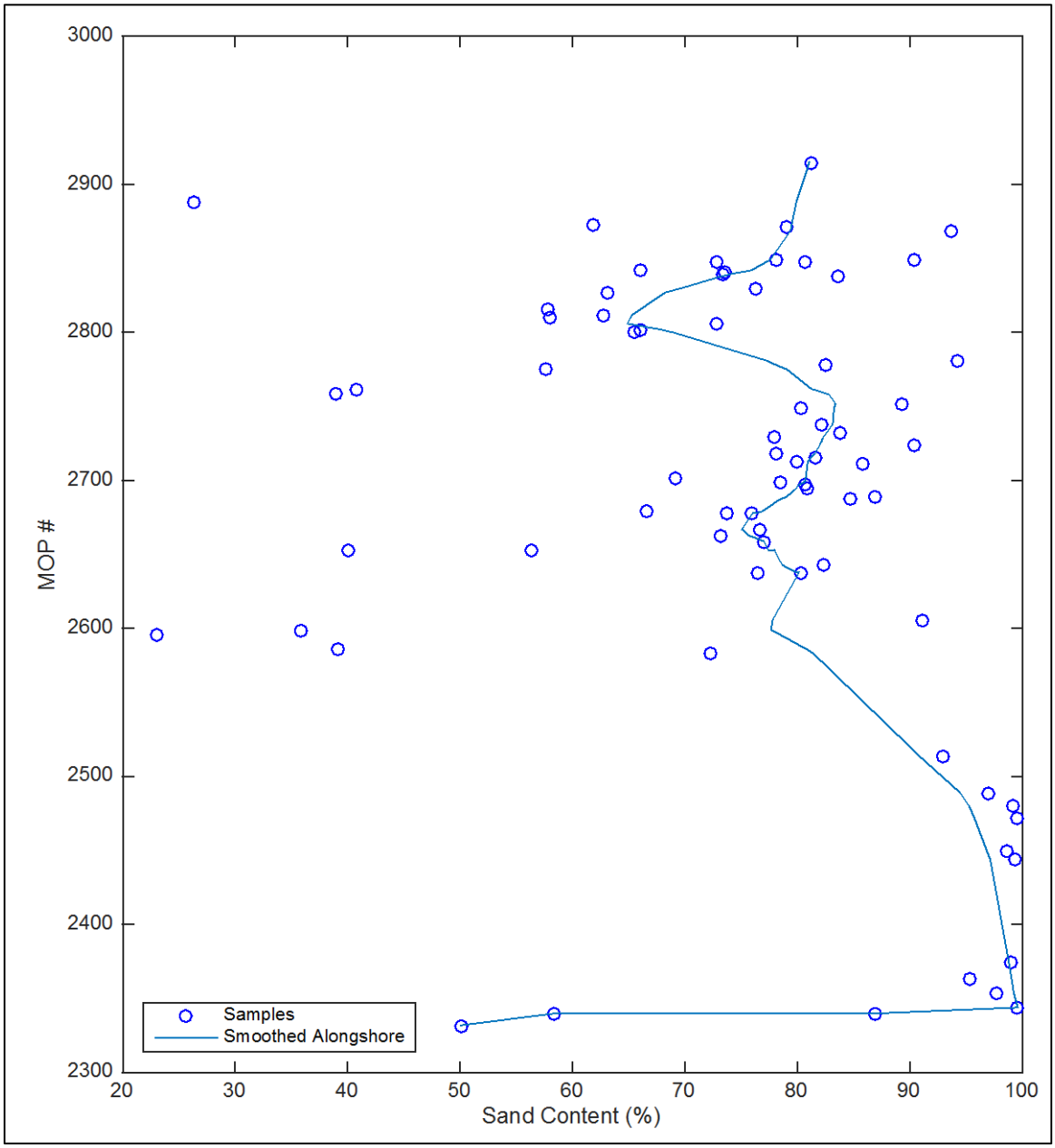

Figure 6. Backshore sand content at sample locations (circles), and smoothed alongshore values used for model input.

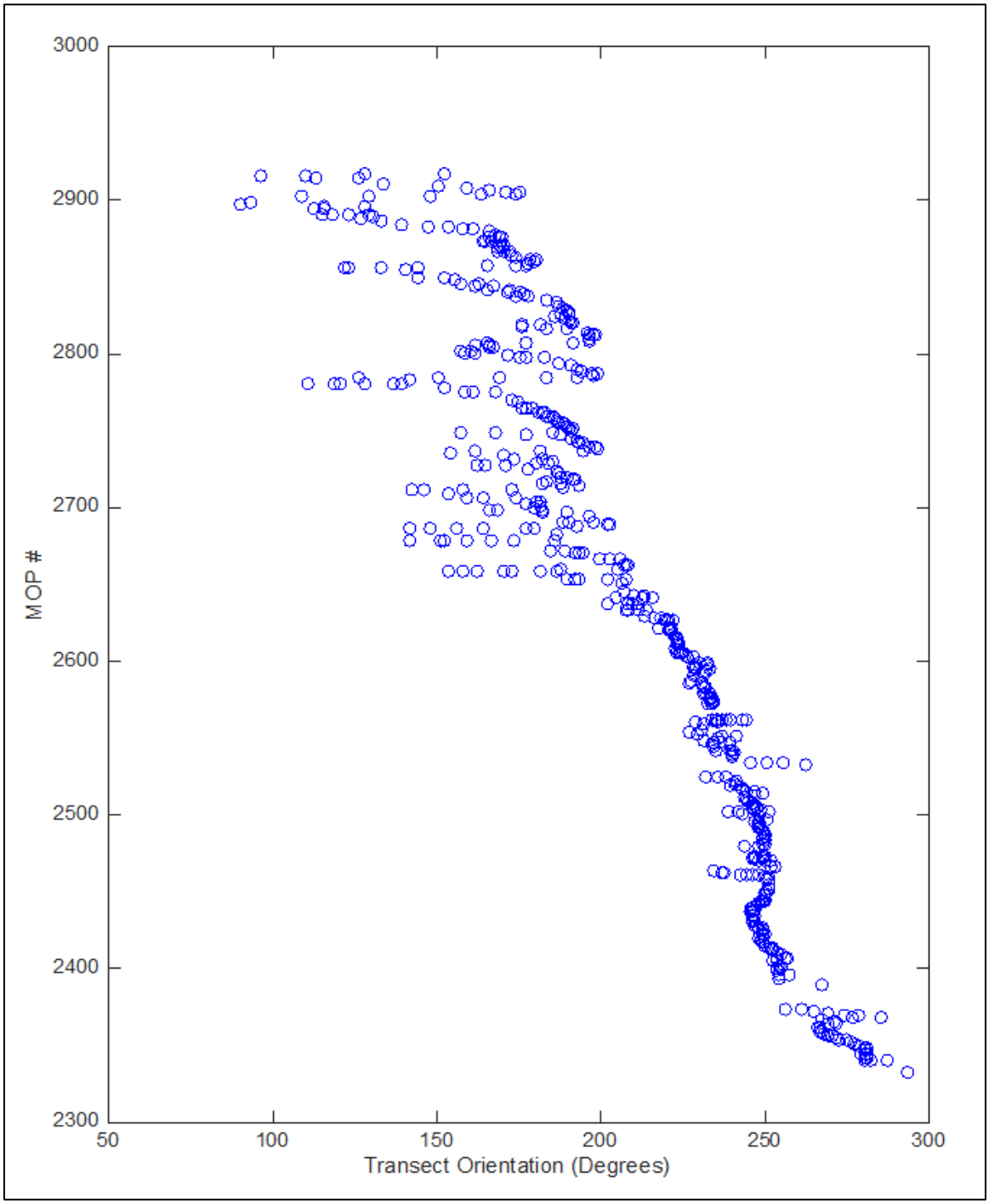

Figure 7. MOP transect orientation.

Figure 8. Beach retreat from sea level rise by 2030, 2050, 2100 for 0.93 m scenario (upper), and 1.67 m scenario (lower), not including wave effects.

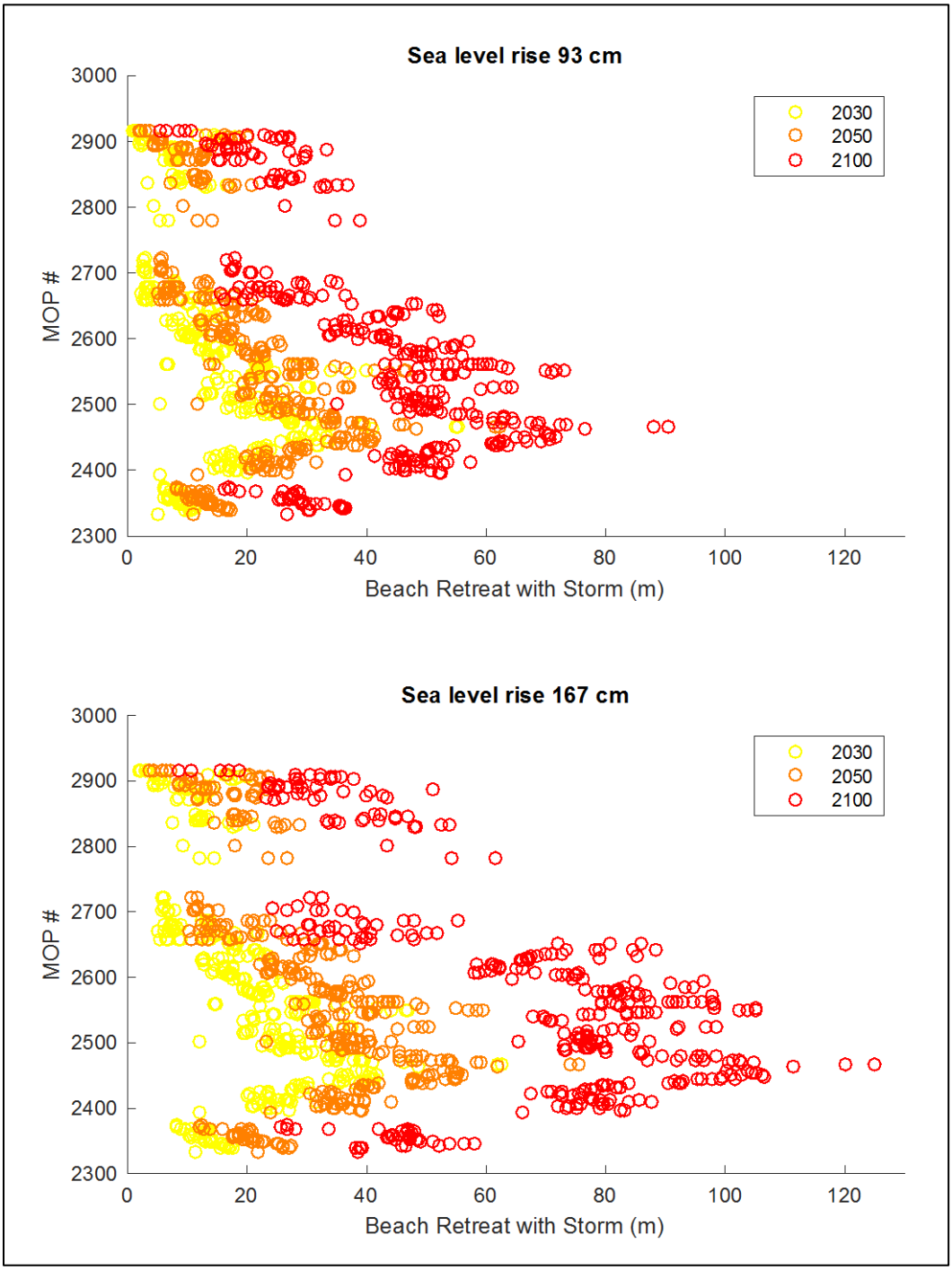

Figure 9. Same as Figure 8, but including sea level rise beach retreat and added maximum storm erosion from Yates *et al.* (2009) shoreline change model.

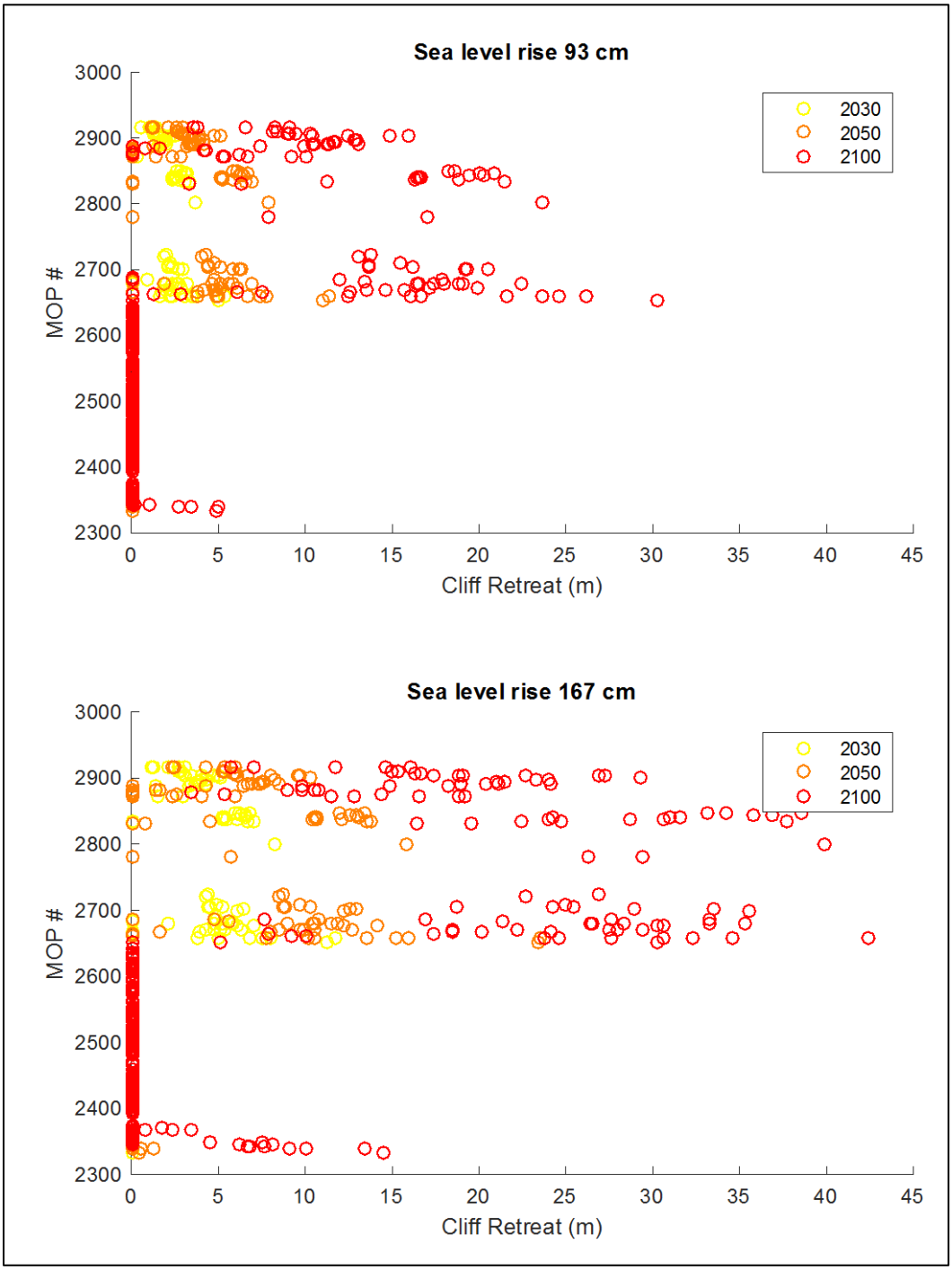

Figure 10. Cliff retreat from sea level rise by 2030, 2050, 2100 for 0.93 m scenario (upper), and 1.67 m scenario (lower).

Figure 11. Shoreline retreat from sea level rise by 2030, 2050, and 2100 for the 1.67 m scenario in the Santa Monica Pier vicinity.

Figure 12. Same as Figure 11 for Malibu east of Pt Dume.

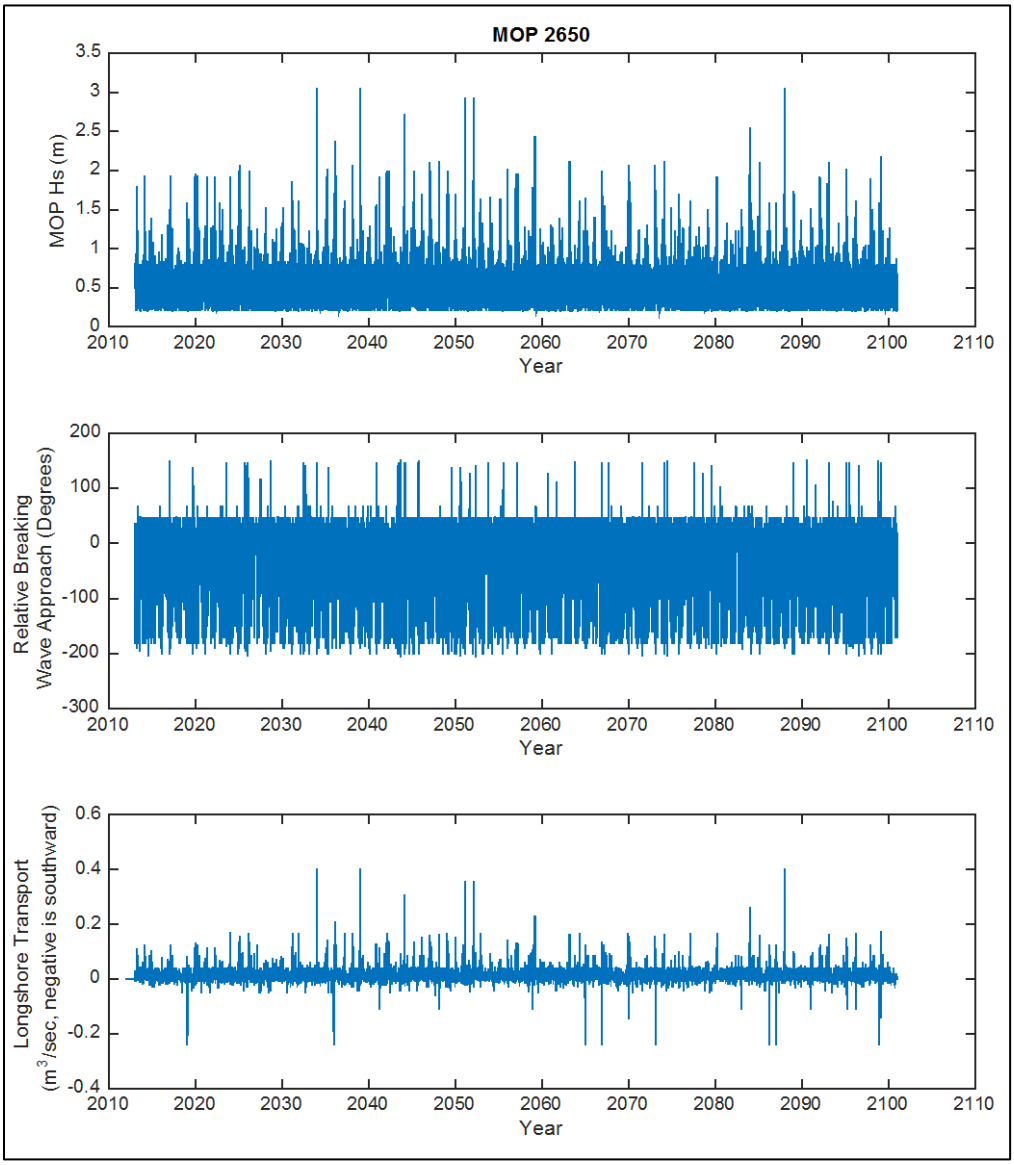

Figure 13. Example of time series of wave height (upper), breaker angle (middle), and model projected longshore sand transport rate from 2012-2100 at MOP 2500.

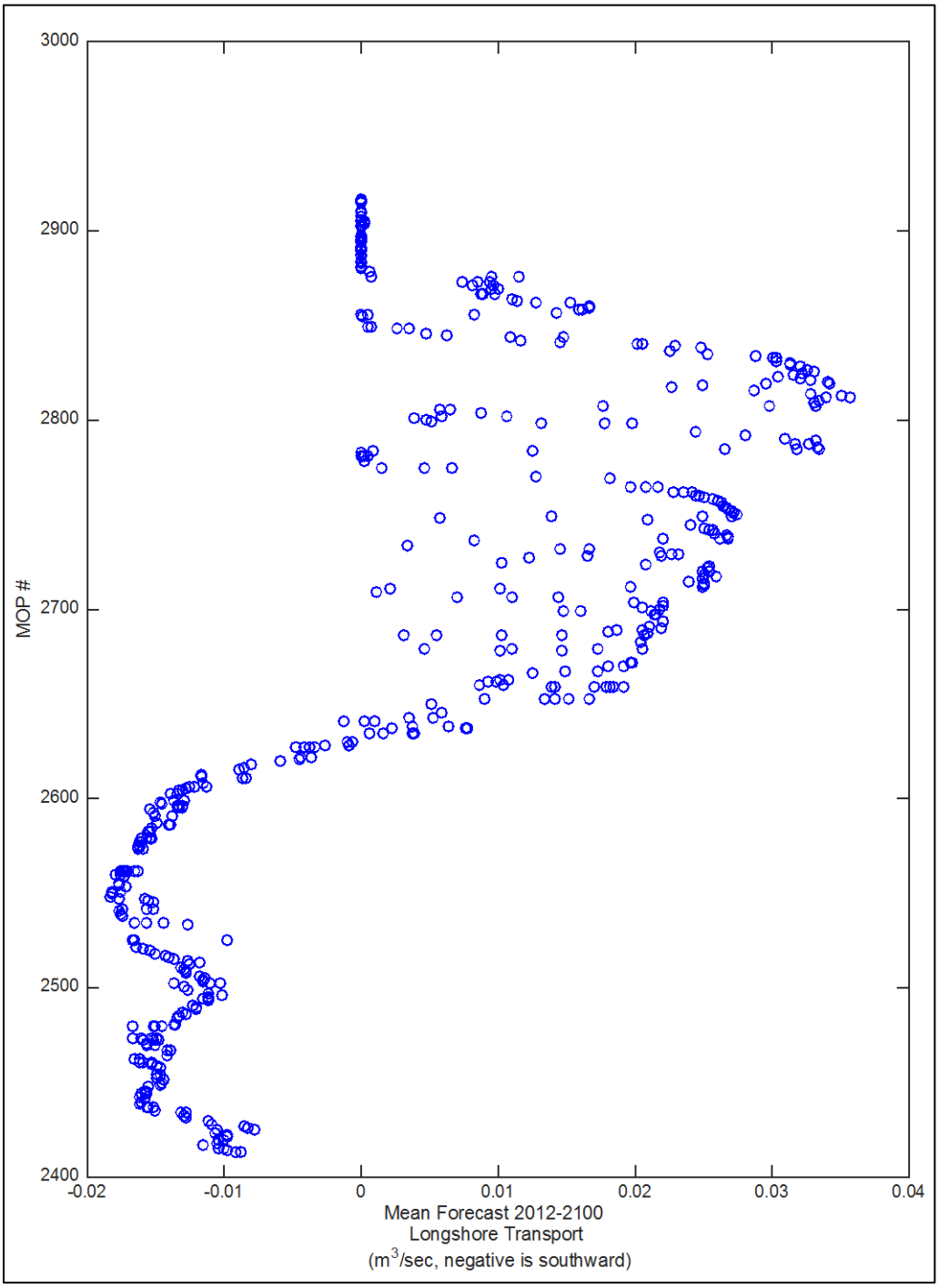

Figure 14. Projected mean longshore sand transport rate averaged from 2012-2100.