

EXTREME SEA-LEVEL PROJECTIONS BASED ON LOCAL WAVES AND FORESHORE SLOPE

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INTRODUCTION

Extreme Sea Levels (ESL) are episodes of infrequent combinations of high tides, storm surges, and waves, also enhanced by the rising of the mean sea level due to Climate Change. These events have the potential to cause devastating flooding, erosion, and inundation, resulting in widespread damage to infrastructure and ecosystems (Oppenheimer et al., 2019). Usually, the future projections of ESL rely only on offshore wave data due to the high computational costs of downscaling multiple Global Climate Models (GCMs) and resolving the required directional and spectral characteristics as waves shoal and refract while approaching the coast. Furthermore, the lack of data for local foreshore slopes restrains the accurate estimation of wave runups (Serafin et al., 2019).

In this study we address these limitations by considering nearshore spectral wave models to compute wave climates in shallow waters and using estimations for the local foreshore slope to compute ESL. From there, we statistically analyse historical and projected scenarios to quantify the amplification factors (AF) of 100-year return period ESL (Oppenheimer et al., 2019). Our case study focuses on Cartagena Bay, Chile (33.3°S, 71.3°W; see Fig.1-a), a 6 km sandy beach embayment, including urbanized areas, and irregular bathymetries (Fig.1-b,c). The bay is exposed to high-energy swells from both the South Pacific and the Northern Hemisphere (Fig.1-d).

METHODS

ESL are computed from the superposition of wave runups (R_2), storm surges (SS), the sea-level rise signal (SLR), and tides (T):

$$ESL = R_2 + SS + SLR + T \quad (1)$$

Data for SLR was sourced from SROCC (Oppenheimer et al. 2019). Wave runup was calculated via Stockdon et al.'s (2006) formula, using nearshore reverse-shoaled waves and beach slope, which was determined by the CoastSat Slope algorithm (Vos et al., 2020). Storm surges were modeled using ADCIRC v55. A mean high semi-diurnal tide of +0.6 masl was chosen for tidal contribution. Wave and storm surge simulations for Cartagena Bay beaches (Fig. 1c) were driven by data from 6 AR5-CMIP5 GCMs under the RCP 8.5 scenario. Additionally, a simplified ESL calculation was performed using offshore wave data and a consistent foreshore beach slope of 0.1, following Melet et al. (2019).

Waves were projected on a 1° Pacific-wide grid for historical (1985-2004), mid-century (2026-2045), and end-century (2081-2100) periods using WAVEWATCH III

v6.07 (WW3MG, 2019). For wave downscaling to Cartagena Bay, we utilized Massel's (1996) method:

$$S(f, \theta^*) = K_a^2(f, \theta) S(f, \theta) \quad (2)$$

$$\theta^* = \theta + \Delta\theta(f, \theta)$$

The transfer functions, K_a and $\Delta\theta$, adjust for energy and directional changes due to nearshore wave propagation. These functions were computed using stationary runs with the STWAVE model, using a unitary wave height ($H_{m0} = 1$) considering several periods and directions. Time series from 6 ensemble GCM sea states were extracted for each beach. For ESL projections, the non-stationary extreme value approach developed by Mentaschi et al. (2016) was employed.

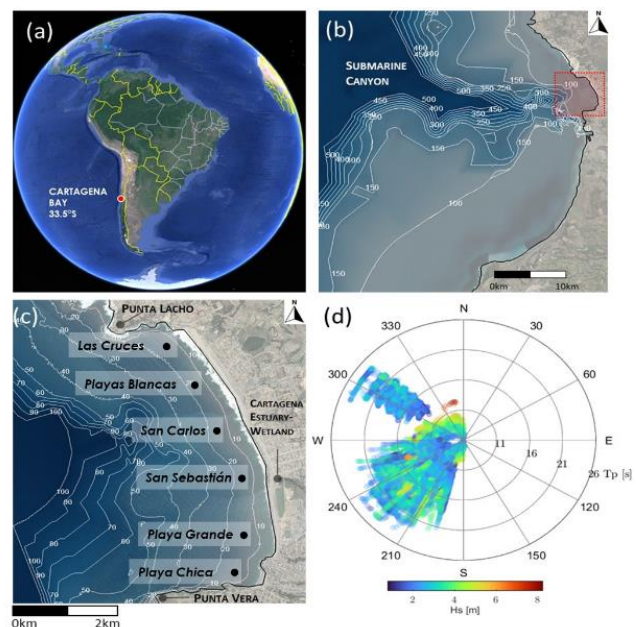


Figure 1 - a) Study site. b) San Antonio Submarine Canyon. c) Cartagena Bay bathymetry and nodes for ESL projections. d) 1985-2021 offshore wave climate directional rose.

Table 1 - GCMs used for wave and storm surge projections.

GCM	Real.	Res.	Developer
		[lat x lon]	
ACCESS 1.0	r1i1p1	1.25 x 1.875	Bureau of Meteorology and CSIRO, Australia
HadGEM-ES	r1i1p1	1.25 x 1.875	Hadley Centre for Climate Science and Services, UK
MIROC5	r1i1p1	1.4 x 1.4	Center for Climate System Research, Japan
MRI-CGCM3	r1i1p1	1.1215 x 1.25	Meteorological Research Institute, Japan
EC-EARTH	r8i1p1	1.1215 x 1.25	European Consortium of National Meteorological Services and Research Institutes
CMCC	r1i1p1	0.75 x 0.75	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy

RESULTS

Figure 2 contrasts the nearshore wave model statistics with ADCP records at 21m depth in Las Cruces from Mar 11 - Apr 25, 2018. While significant wave heights are slightly overestimated, Massel's method accurately captures variations in wave periods and directions.

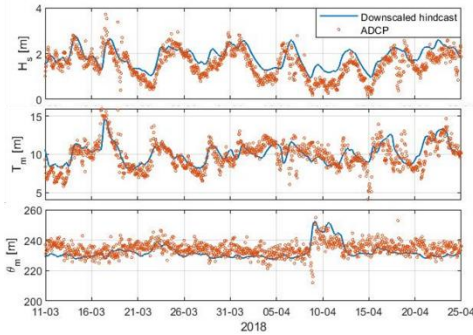


Figure 2 - March-April 2018 Las Cruces, Cartagena Bay data: Nearshore wave model statistics and ADCP. Significant wave heights (a), mean wave periods (b), mean wave directions (e).

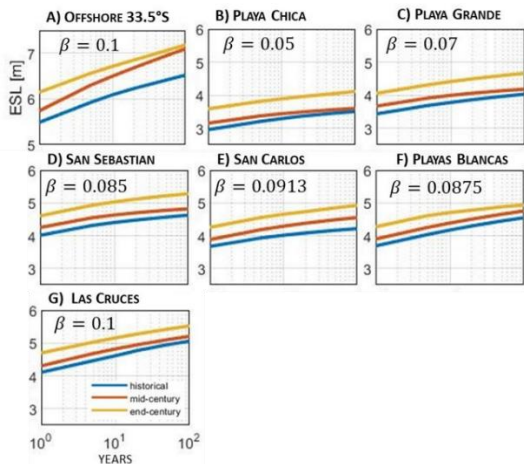


Figure 3 - Median GCM ensemble of ESL recurrence at Cartagena Bay using offshore (a) and nearshore wave parameters (b-g) determined by non-stationary extreme value analysis.

Figure 3 illustrates disparities in offshore and nearshore ESL projections, with offshore ESL values tending to overestimate. Playa Chica exhibits lower ESL values due to its natural shelter and gentle slope, whereas Las Cruces presents higher ESL values owing to its steeper slope and southwest wave exposure. In addition, recurrence curves indicate a uniform increase in ESL towards the end-century. Table 2 shows mid-century projections, with San Carlos and Playa Chica having the largest and smallest 100-year ESL increases at +0.34 m and +0.10 m, respectively. For end-century projections, Playas Blancas and San Carlos exhibit the lowest and highest values at +0.39 m and +0.71 m, respectively. By the end-century, nearshore AF values at Playa Chica, Playa Grande, and San Carlos suggest the future frequency of 100-year ESL events will shift to annually event. Conversely, for offshore-based ESL projections,

Playas Blancas and Las Cruces display lower AF values of 21.6, 23.4, and 15.9. This shifts 100-year ESL events to occur every 4.6, 4.2, and 6.2 years, respectively.

Table 2. GCM ensemble median of 100 return periods ESL (ESL^{100Y}) offshore and on the six beaches analyzed.

	ESL ^{100y} [m] (projected changes)			Amplification Factor (AF)	
	Hist	Mid	End	Mid	End
Offshore	6.52	7.11 (+0.58)	7.18 (+0.66)	8.8	21.6
Playa Chica	3.51	3.62 (+0.10)	4.12 (+0.61)	4.2	117.2
Playa Grande	4.03	4.18 (+0.15)	4.66 (+0.63)	6.4	103.9
San Sebastián	4.63	4.82 (+0.19)	5.28 (+0.65)	10.6	78.7
San Carlos	4.21	4.55 (+0.34)	4.92 (+0.71)	15.7	105.8
Playas Blancas	4.55	4.76 (+0.21)	4.94 (+0.39)	3.5	23.4
Las Cruces	5.06	5.21 (+0.15)	5.52 (+0.46)	2.4	15.9

CONCLUSION

This study highlights Cartagena Bay's vulnerability to ESL events under a high-emission scenario. Nonetheless, ESL projections across different beaches show variations, influenced by factors such as nearshore wave climate and foreshore beach slope. We emphasise that accurate ESL projections necessitate wave downscaling grounded in the wave spectrum, along with a thorough consideration of the foreshore slope. Relying solely on integrated parameters might omit essential information, complicating nearshore ESL hotspot identification. Massel's approach efficiently handles the downscaling of multi-model GCMs. Finally, we recommend that international initiatives for wave projections like COWCLIP, try to incorporate directional wave spectrum or wave partitions to enhance nearshore ESL hotspot detection, especially in closed bays with irregular bathymetries and submarine canyons.

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