

SINGLE EXTREME STORM SEQUENCE CAN OFFSET DECADES OF SHORELINE RETREAT PROJECTED TO RESULT FROM SEA-LEVEL RISE

Mitchell D. Harley^{1*}, Gerd Masselink², Amaia Ruiz de Alegría-Arzaburu³, Nieves G. Valiente^{2,4}, Tim Scott²

¹Water Research Laboratory, School of Civil and Environmental Engineering, UNSW Sydney, Manly Vale, Australia
m.harley@unsw.edu.au

²Coastal Processes Research Group, School of Biological and Marine Sciences, University of Plymouth, Plymouth, United Kingdom

³Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, Ensenada, Mexico

⁴Met Office, Exeter, United Kingdom

Abstract

Extreme storms cause extensive beach-dune erosion and are typically considered to enhance coastal erosion due to sea-level rise. However, extreme storms can also have a positive contribution to the nearshore sediment budget by exchanging sediment between the lower and upper shoreface and/or between adjacent headlands, potentially mitigating some adverse sea-level rise impacts. Here we use three high-resolution morphological datasets of extreme storm-recovery sequences from Australia, the UK and Mexico to quantify the nearshore sediment budget and relate these episodic volume changes to long-term coastal projections. We show that sediment gains over the upper shoreface were large (59–140 m³/m) and sufficient to theoretically offset decades of projected shoreline retreat due to sea-level rise, even for a high-end greenhouse gas emissions scenario (SSP5-8.5). We conclude that increased confidence in shoreline projections relies fundamentally on a robust quantitative understanding of the sediment budget, including any major short-term sediment contribution by extreme storms.

Introduction

Climate change is likely to cause a global sea-level rise (SLR) by 2100 of 0.63–1.01 m based on a high-end greenhouse gas emissions scenario (SSP5-8.5)¹. Combined with ambient trends in shoreline dynamics, SLR under this scenario has been projected (using an approach known as the Bruun rule²) to result in a large retreat or loss of almost half of the world's sandy beaches by the end of this century³. Climate change has also been predicted to drive increases in extreme wave heights along almost three fifths of the world's coastline by the end of the century⁴, but the long-term (> 50 years) impact of extreme storms on coastal recession – and its coupling with SLR – is ambiguous. Increased storminess is generally assumed to exacerbate coastal erosion due to SLR; however, short-to-medium term (years–decades) shoreline variability caused by storms is generally considered noise over long time scales when shoreline change is mainly driven by SLR^{5,6}. On the other hand, extreme storms can transport sediment into the nearshore zone from elsewhere, for example from the lower shoreface⁷, potentially tempering long-term erosion by SLR^{8,9}.

37 Despite its many assumptions and shortcomings^{10,11}, the Bruun rule has emerged as the most widely used method
38 for predicting shoreline change due to SLR⁶, for localized coastal hazard assessments¹² as well as in global studies^{3,13}.
39 In its most simple and original form, the Bruun rule reduces to $R = S/\tan\beta$, where R is shoreline retreat, S is sea-level
40 rise and $\tan\beta$ is the upper shoreface gradient. Application of the Bruun rule involves a simple upward and backward
41 translation of the shoreface profile to a location where the volumetric losses from the upper part of the profile are
42 matched by the gains across the lower part. Sediment gains and losses can be included in the Bruun rule^{14,15}, but
43 their inclusion requires a rigorous insight into the nearshore sediment budget¹⁶ as the cross-shore and longshore
44 sediment fluxes, sediment production and anthropogenic contribution all play a key role in the coastal response. Of
45 particular relevance in this context is the impact of extreme storm activity on the sediment budget, as it is under
46 these forcing conditions that sediment fluxes are maximized and the impact of the sediment budget on long-term
47 shoreline change is potentially greatest.

48
49 Coastal erosion and shoreline retreat as a result of extreme storm activity is particularly apparent on the upper
50 beach as storm waves leave beaches depleted and coastal dunes scarped, with typical beach-dune sediment losses
51 of 50–150 m³ per unit meter beach width^{17–19}. A suite of cross-shore and longshore sediment transport pathways are
52 responsible for these morphological changes, summarized in Figure 1. The vast majority of sediment transport
53 pathways during both extreme and non-energetic (i.e., modal) wave conditions merely redistribute sediment across
54 the upper shoreface, i.e., landward of the depth of closure (DoC), defined as the depth beyond which no detectable
55 morphological change occurs over a given timeframe^{20–22}. Sediment exchange between the lower and upper
56 shoreface across the DoC can, however, play an important role in long-term shoreline change, and of particular
57 interest here is the wave-driven onshore sediment transport driven by disequilibrium shoreface morphology^{7,9}.

58
59 Geological evidence from Australia strongly suggests that low-magnitude onshore sediment transport $O(1 \text{ m}^3/\text{m}/\text{yr})$
60 from the lower shoreface to the beach has been responsible for extensive coastal progradation when sea level was
61 relatively stable throughout the mid to late Holocene^{23–25} (see also examples from Brazil²⁶ and The Netherlands²⁷).
62 Under the influence of rising sea level, this component, which results in a lowering of the lower shoreface as
63 sediment is transported onshore²⁸, has the potential to offset, or even overturn, the impact of sea-level rise¹⁴. As the
64 source of this sediment is beyond the DoC, it is highly likely that energetic wave conditions are implicated in this
65 transport, as modal waves are not expected to be able to move sediments at such depths. Onshore-skewed
66 oscillatory motions on the seabed caused by wave nonlinearity are able to act at much greater depths during
67 energetic conditions, providing a mechanism for suspended and bedload sediment transport from the lower to
68 upper shoreface²⁹. Net shoreface sand supply to beaches may be a widespread and common, but little appreciated
69 factor in coastal stability^{30,31}. Likewise, sediment from adjacent beaches and mobilised during extreme storms (e.g.,
70 headland sand bypassing) may provide an additional source of sediment to the nearshore region^{32–34}.

71
72 This paper presents three unique coastal morphological data sets from three different continents (Australia, Europe
73 and North America, refer Figure 2) that each encompass a sequence of an extreme storm or extended storm cluster
74 followed by a milder period of beach recovery. Despite the morphological data being collected beyond the

75 theoretical DoC, sediment budget analysis unequivocally points towards unbalanced sediment budgets at all three
76 sites, demonstrating in these cases large sediment gains within the upper shoreface over the storm-recovery
77 sequence. We show that these short time-scale events can have important implications for long-term coastal
78 evolution and, when placed in the context of projections undertaken using the common Bruun rule approach, can
79 theoretically offset decades of predicted shoreline retreat due to SLR, even under a high-range greenhouse gas
80 emissions scenario (SSP5-8.5). Our results highlight major limitations of the Bruun rule approach for long-term
81 coastal projections and emphasize the need for enhanced shoreface monitoring worldwide to better quantify
82 changes in sediment budgets due to climate change.

84 Results

85 Figures 3-5 summarize long-term and extreme storm sequence results at three high-resolution coastal monitoring
86 locations in Australia, the UK and Mexico. These three locations are: (1) the 3.6 km-long Narrabeen embayment in SE
87 Australia (Figure 3), comprising one of the longest (> 40 years, monthly) subaerial beach survey programs
88 worldwide³⁵; (2) the 3.5 km-long Perranporth embayment in SW England (Figure 4), where monthly subaerial beach
89 surveys have been undertaken monthly since 2006³⁶; and (3) the open-coast La Misión Beach in NW Mexico (Figure
90 5), where a 2.2-km stretch of sandy coast has been monitored monthly since 2015. Each site is characterized as
91 wave-dominated (average $H_s \approx 1.6$ m at all three sites), sandy ($D_{50} \approx 0.3$ – 0.4 mm) and of moderate upper shoreface
92 steepness ($\tan\beta, \approx 0.03$ – 0.04). The tidal regimes at Narrabeen and La Misión are microtidal (spring tidal range = 1.3
93 and 2.3 m, respectively), whereas Perranporth is macrotidal (spring tidal range = 6.3 m).

94 Complementing the continuous subaerial beach measurement records (including dune systems if present) were
95 detailed three-dimensional surveys of the entire upper shoreface at time intervals prior to, immediately following
96 and approximately 12 months after an extreme storm event or extended storm cluster. At Narrabeen, an extreme
97 east coast low storm impacted the coast in June 2016 that resulted in the largest subaerial beach erosion (average =
98 $121 \text{ m}^3/\text{m}$) over four decades¹⁹. At Perranporth, a cluster of extratropical cyclones over successive boreal winters
99 between 2013 and 2016 caused an average of $212 \text{ m}^3/\text{m}$ of subaerial beach erosion, with the 2013/2014 winter
100 period in particular considered the most energetic winter period since at least 1948¹⁸. At La Misión, a similar
101 sequence of extratropical storms concentrated over the 2018/2019 boreal winter caused the most severe winter
102 erosion (average = $208 \text{ m}^3/\text{m}$) since measurements at the site began (Figure 5b). Each three-dimensional survey
103 extended from the upper beach to beyond the theoretical DoC over the respective storm sequences, calculated (see
104 Methods) as -11.6 m (Narrabeen), -19.3 m (Perranporth) and -9.1 m (La Misión), all referenced to mean sea level
105 (MSL).

106 The morphological response from all three storm sequences indicates patterns of extensive erosion along the
107 subaerial beach coupled with adjacent sediment deposition in the shallow subaqueous zone. Representative cross-
108 shore transects (Figures 3g, 4e and 5e) show these deposition zones are characterized by pronounced storm bar
109 morphology with bar crests between approximately 200 m offshore for the microtidal Narrabeen site and 700 m for
110 the macrotidal Perranporth site. Pivot points separating areas of upper-shoreface storm erosion and deposition are
111 observed at depths relative to MSL of approximately -2.9 m (Narrabeen), -5.8 m (Perranporth) and -1.2 m (La

112 Misión). In the subsequent recovery phase, eroded sediment stored in the storm bar returns under more modal
113 wave conditions, and the patterns of storm erosion and deposition are mostly reversed. At lower depths, profile
114 variability displays the characteristic 'pinching' towards the theoretical DoC that is typical of the upper shoreface,
115 although seabed variability outside of the survey error (~ 0.14 m) is still evident at these lower depths.

116 Integrating these observations over the upper shoreface and beach, whilst carefully considering survey error (refer
117 Methods), reveals that the overall sediment balances are not closed and all three locations record large net
118 sediment gains over the storm-recovery sequence (Figure 6). Average net gains per unit meter beach width range
119 from $+59$ m^3/m (La Misión) to $+140$ m^3/m (Perranporth), which are comparable in magnitude to the extreme erosion
120 observed over the subaerial beach during each storm sequence. In absolute terms, within the three-dimensional
121 survey areas spanning several kilometres, these sediment gains equate to $+130\,000$ m^3 of sediment (La Misión),
122 $+400\,000$ m^3 (Narrabeen) and $+420\,000$ m^3 (Perranporth). While the direct source of these sediment gains cannot be
123 conclusively ascertained without detailed process-based measurements and tracer experiments, the alongshore
124 variability and phasing of these net gains provide some insight into the sediment pathways (using Figure 1 for
125 reference). At Narrabeen, sediment gains occurred primarily in the storm phase and are strongly skewed towards
126 the southern half of the embayment (max. net gain = $+392$ m^3/m). This is consistent with likely counter-clockwise
127 beach rotation (Transport Pathway 3 in Figure 1) caused by this anomalous easterly storm^{19,37}, but also coincides
128 with the region of the rocky embayment where lower shoreface sand bodies (i.e., beyond the DoC) are more
129 abundant³⁸, suggesting onshore sediment transport from the lower to upper shoreface (Pathway 6). At Perranporth,
130 sediment gains occurred instead primarily over the recovery phase and particularly at the southern half (max. net
131 gain = $+271$ m^3/m), which might be related to alongshore headland sand bypassing input at the southern extremity
132 (Pathway 1) under less-extreme winter periods that have been shown to enhance beach recovery³². Similar to
133 Narrabeen, sediment gains at La Misión occur primarily over the storm phase, but unlike the embayed Narrabeen
134 and Perranporth sites, shows no obvious alongshore bias (max. gain = $+309$ m^3/m). Possible sediment sources for
135 these net gains include onshore sediment transport from lower shoreface sand storages (Pathway 6), as well as
136 winter fluvial discharges from the nearby tidal inlet (Pathway 7).

137 The observed sediment gains over the entire upper shoreface and beach are subsequently characterized in terms of
138 equivalent years of theoretical shoreline retreat predicted by the Bruun rule under various emission scenarios¹,
139 thereby evaluating the potential for substantial errors in shoreline predictions due to SLR using the Bruun rule
140 approach¹⁴. Figure 6b shows that the annual rate of sediment input required to theoretically offset 21st Century
141 (2000–2100) SLR recession as predicted by the Bruun rule (Q_{offset}) is a function of the upper shoreface width W^* ,
142 defined as the horizontal distance from the subaerial beach berm to the DoC. Here we use the long-term DoC
143 derived from 41 years of wave reanalysis data (see Methods), rather than over the DoC calculated over the shorter-
144 term storm-sequence as above²⁸. For Narrabeen, the narrower upper shoreface width (long term DoC = -14.3 m,
145 $W^* = 480$ m) means that this offset rate equates to 3.7 $\text{m}^3/\text{m}/\text{year}$ for SLR estimated under an upper SSP5-8.5
146 emissions scenario between 2000 and 2100, compared to 6.2 and 8.4 $\text{m}^3/\text{m}/\text{year}$ for the deeper and wider La Misión
147 and Perranporth upper shorefaces (long term DoC = -18.2 m and -20.2 m, $W^* = 810$ m and 1090 m for La Misión and
148 Perranporth, respectively). Based on these annual rates, the observed sediment gains over the extreme storm-

149 recovery sequence at Narrabeen are equivalent to 25 years of SLR recession predicted by the Bruun rule that may be
150 theoretically offset at the upper SSP5-8.5 scenario, or 43 years for the more sustainable SSP1-2.6 emissions scenario.
151 At Perranporth and La Misi3n, these sediment gains equate to 18 and 10 years for SSP5-8.5, or 31 and 17 years for
152 SSP1-2.6, respectively.

153 Discussion

154 Our results based on unique high-resolution field measurements over three extreme storm-recovery sequences from
155 three different continents highlight the present major challenges of predicting long-term coastal evolution over
156 planning horizons of decades to centuries. Whereas long-term modelling approaches typically assume short-term
157 sediment losses on the subaerial beach and dune caused by extreme storm sequences are balanced by sediment
158 gains in the subaqueous zone (resulting in zero net change in the sediment budget), our results indicate large net
159 positive sediment gains integrated over the entire upper shoreface. Furthermore, the magnitude of these observed
160 net gains – which primarily manifest at depths from MSL down to the DoC – are commensurate ($O(100\text{ m}^3/\text{m})$) to the
161 extreme erosion that is highly visible (and widely-reported^{18,19}) on the subaerial beach and dune during these
162 extreme events. Likewise, these magnitudes equate to typical volumes undertaken for artificial beach nourishment
163 projects³⁹ and, when expressed in terms of Bruun-rule predicted shoreline change, are equivalent to offsetting
164 decades of predicted shoreline retreat, even under an upper-range emissions scenario (SSP5-8.5). This highlights the
165 potential for a cascading of model prediction error using the Bruun rule and other simplified approaches (e.g.,^{9,23})
166 that do not implicitly include storm-driven sediment fluxes, placing additional concern^{10,11} regarding their validity for
167 long-term prediction. This is particularly in light of robust projections pointing towards an increase in extreme waves
168 along almost three fifths of the world coastline⁴, implying an exacerbation of episodic major sediment exchange
169 between the lower and upper shoreface, and/or alongshore adjacent embayments, in the coming decades that could
170 significantly alter long-term coastal evolution.

171
172 Whether these observed major short-term net sediment gains to the upper shoreface and beach are relatively
173 common, or indicative of the extreme nature of these particular storm sequences, is presently difficult to ascertain.
174 Each storm sequence is characterized by extreme subaerial beach erosion that equates to the largest short-term
175 erosion volumes observed in this upper part of the beach over their respective measurement records (refer Figures
176 3c, 4b and 5b). At lower depths, however, the potential for major wave-driven sediment transport across the DoC
177 (i.e., Pathway 6 in Figure 1) can be evaluated by estimating wave orbital velocities (U_{rms}) at the seabed corresponding
178 to the long-term DoC (see Methods). This simple approach provides a first-order assessment of sediment transport
179 potential, while recognising that processes such as longshore sediment transport and headland bypassing (Pathway
180 1), upwelling and/or tidal currents (Pathway 9) and estuarine/fluvi al inputs (Pathway 7) may all play a key role^{22,29}.
181 Figure 7 indicates that for the three respective storm sequences, wave orbital velocities at these depths are
182 estimated to have reached up to 1.2 m/s (Perranporth), 1.0 m/s (Narrabeen) and 0.6 m/s (La Misi3n), which are well
183 above the typical threshold of motion for shoreface sediment ($U_{crit} \approx 0.2\text{ m/s}$, see Methods) and suggest large
184 sediment transport potential. Over the longer-term (1979–2020) dataset, these equivalent wave orbital velocities
185 are estimated to occur only rarely at Perranporth and Narrabeen where the largest net sediment gains were

186 observed ($\Delta V = +140 \text{ m}^3/\text{m}$ and $+91 \text{ m}^3/\text{m}$, respectively), having been exceeded just 9 hours over the 41-year record
187 at Perranporth (i.e., $U_{rms} > 1.2 \text{ m/s}$) and 91 hours at Narrabeen ($U_{rms} > 1.0 \text{ m/s}$). At La Misión, where observed net
188 sediment gains were the smaller of the three sites ($\Delta V = +59 \text{ m}^3/\text{m}$), equivalent wave orbital velocities are estimated
189 to occur more frequently over the historical record (636 hours over the 41 years, $U_{rms} > 0.6 \text{ m/s}$). This suggests a
190 potential scaling between sediment transport potential (estimated by the wave orbital velocity at the DoC) and the
191 magnitude of short-term net sediment gains caused by storm-recovery sequences, with less-frequent events
192 potentially resulting in a larger sediment influx. A notable example evident in the historical dataset at La Misión is
193 the January 1988 storm (maximum $U_{rms} = 1.4 \text{ m/s}$, Figure 7c) that resulted in extreme coastal impacts at nearby
194 Southern California, including reported *in situ* observations⁴⁰ of large seabed changes extending down to depths of -
195 25 m.

196
197 Further evidence as to the historical frequency of these major short-term net sediment gains can be garnered from
198 the long-term subaerial volume measurements. Considering the Narrabeen beach monitoring program that spans 44
199 years of continuous subaerial beach measurements³⁵, the subaerial beach volume data (Figure 3c) indicate no
200 significant long-term erosion or accretion trend (linear regression trend = $-0.08 \pm 0.11 \text{ m}^3/\text{m}/\text{year}$). Similar to the
201 wave orbital velocity analysis above, this suggests that similar short-term sediment gains as observed over the 2016-
202 2017 storm-recovery sequence at this site have either: (1) occurred very rarely; (2) do not have a noticeable
203 subaerial beach signature (i.e., sediment gains do not move sufficiently onshore to be observed on the subaerial
204 beach); have been balanced by equivalent sediment losses (e.g., Pathways 1, 7, 8 and 9 in Figure 1); or (3) have
205 possibly contributed to offsetting the approximately 0.10 m of relative SLR that has occurred over this 44-year
206 record⁴¹. At Perranporth and La Misión, the subaerial beach volume data suggest a slight erosional trend at
207 Perranporth (linear regression trend = $-5.3 \pm 2.9 \text{ m}^3/\text{m}/\text{year}$) and a relatively strong accretionary trend at La Misión
208 (linear regression trend = $23.3 \pm 16.8 \text{ m}^3/\text{m}/\text{year}$), although it is likely that these shorter-term records are biased by
209 the storm sequences themselves.

210
211 While each of the three datasets show net positive sediment contributions, equally plausible on sandy coastlines
212 more generally are extreme storm sequences that cause major losses to the overall sediment budget (e.g.
213 imbalances in Pathways 1, 7, 8 and 9 in Figure 1). Short-term sediment fluxes between the lower and upper
214 shoreface (across the DoC) and from adjacent beaches reflect complex interactions between sediment transport
215 processes, sediment storage (both on the lower shoreface and at adjacent beaches) and accommodation space
216 between the lower and upper shoreface. As outlined in two recent reviews of shoreface morphodynamics^{29,42}, the
217 present conceptual understanding of sediment transport on the lower shoreface is extremely limited. This is due to a
218 combination of many factors, including: subtle imbalances between onshore and offshore-directed sediment fluxes;
219 the dominance of bed load and gravity flows at these depths; the presence of migrating bedforms; a paucity of field
220 data measurements beyond the surf zone; and uncertainties associated with up-scaling short-term measurements
221 and process understanding to longer time scales. These limitations are compounded by the severe lack of any
222 knowledge of the seabed composition on the lower shoreface, with estimates suggesting that 71% of ocean depths
223 between the MSL and -200 m depth contours remain completely uncharted⁴³.

224

225 Predicting the potential fate of coastal environments out to the year 2100 and beyond, i.e., forecasting the 2100
226 coastline, is one of the most pressing challenges facing coastal science today. While it is unlikely that a step-change
227 in our ability to model sediment transport at and between the lower and upper shoreface will be achieved in the
228 near future, significant improvements in long-term predictions can be realised through: (1) a major upscaling of
229 seabed mapping efforts (e.g. ^{44,45}) to evaluate the magnitude of sediment presently stored on the lower shoreface;
230 and (2) a significantly greater number of routine monitoring efforts of entire nearshore systems appropriate for
231 quantifying sediment fluxes. These two steps can greatly help identify both short and long-term changes to sediment
232 budgets and their connectivity between lower and upper shoreface (including dunes), and between adjacent
233 embayments, as well as provide early warning for coastal communities of any large-scale sediment shifts to SLR in
234 the coming decades. The latter is particularly important considering potential coastal barrier overstepping and
235 dramatic shoreline change under very rapid sea-level rise scenarios, as has been observed in the mid-Holocene⁴⁶.
236 Improvements in remote sensing technology (e.g. satellite-derived bathymetry⁴⁷) are also likely to complement
237 shoreface monitoring efforts, by providing regional perspectives on entire sediment compartments and their
238 linkages⁴⁸. However, the vertical accuracies of these technologies are still limited ($\sigma_v > 0.4$ m), re-emphasising the
239 need for enhanced traditional *in-situ* monitoring strategies⁴⁹.

240

241 **Methods**

242 *Multimethod morphological surveys*

243 Morphological surveys at each of the three locations were undertaken using a combination of survey methods to
244 ensure seamless digital elevation models (DEMs) spanning the subaerial and subaqueous beach system. At
245 Narrabeen, subaerial beach surveys were undertaken using Airborne Lidar and Uncrewed Aerial Vehicles (UAVs),
246 with vertical uncertainty (σ_v) quantified for this site and equipment as 0.11 m and 0.07 m, respectively^{50,51}. At
247 Perranporth, subaerial beach surveys were undertaken using a combination of Airborne Lidar ($\sigma_v = 0.15$ m) and
248 either UAV ($\sigma_v = 0.06$ m at this site) or RTK-GNSS mounted to an ATV ($\sigma_v = 0.05$ m)³². At La Misión, subaerial beach
249 surveys were undertaken by walking RTK-GNSS ($\sigma_v = 0.05$ m) at 50-m spaced cross-shore transects. At all three sites,
250 subaqueous surveys were undertaken using a single beam echosounder mounted on a boat (Perranporth, $\sigma_v =$
251 0.05 m) or jetski (Narrabeen and La Misión, $\sigma_v = 0.10$ m). These depth soundings were collected near-continuously
252 along cross-shore transects spaced every 50 m at Narrabeen and Perranporth, or every 150 m at La Misión. At
253 Perranporth, surveys were also complemented in deeper water (< -10 m) by multibeam echosounder ($\sigma_v = 0.06$ –
254 0.30 m)³². Seamless DEMs were subsequently created from the multimethod surveys using cubic interpolation. This
255 method was found to best represent natural beach variability (e.g. intertidal bars) in the small data gaps (<30 m
256 cross-shore) between subaerial and subaqueous measurements found at the microtidal Narrabeen and La Misión
257 sites.

258 *Sediment budget error analysis*

259 DEMs of Difference (DoD), characterizing spatial variability in beach elevation change at each site, were calculated
 260 from the individual DEMs described above. Sediment budget error analyses were calculated following the approach
 261 of⁵², by first considering the limit of detection (*LoD*) for each DEM grid point:

$$LoD = \sqrt{\sigma_{DEM1}^2 + \sigma_{DEM2}^2}$$

262 where σ_{DEM} is the vertical uncertainty at each grid point depending on the localized survey method. The overall
 263 volume change ΔV and associated uncertainty for each DoD were then calculated by considering only statistically-
 264 significant (95% confidence level) morphological change above the limit of detection ($|Z_{DEM1} - Z_{DEM2}| > LoD$).
 265 These overall volume changes ΔV were then normalized per unit beach width based on the number of cross-shore
 266 transects in the survey region.

267 *Equivalent years of SLR recession theoretically offset using the Bruun rule*

268 Volumetric changes to the sediment budget caused by the three storm sequences were converted to equivalent
 269 years of SLR recession that may be theoretically offset over the 21st Century when estimated using the Bruun rule, in
 270 order to evaluate the potential for large error using this simple approach. Upper shoreface widths W^* were
 271 calculated at each site considering the alongshore-averaged horizontal distance between the subaerial beach berm
 272 and the long-term *DoC*, which is calculated relative to mean low water as^{21,53}:

$$DoC = 2.28H_{s,Y} - 68.5 \left(\frac{H_{s,Y}^2}{gT_{p,Y}^2} \right)$$

273 where $H_{s,Y}$ is the significant wave height exceeded 12 hours every Y years, g is gravity and $T_{p,Y}$ the associated peak
 274 wave period. Following other SLR estimates using the Bruun rule (e.g.,^{3,13}), ERA5 wave reanalysis data⁵⁴ spanning 41
 275 years (1979–2020) was used to calculate the long-term *DoC* at each site. These values relative to mean low water
 276 were then converted to MSL considering the tidal range. The annual rate of sediment input required to theoretically
 277 offset SLR recession using the Bruun rule (Q_{offset}) is subsequently calculated by:

$$Q_{offset} = \frac{S}{Y} W^*$$

278 where S is the predicted median change in sea level over the 21st Century¹ ($S = 0.44$ m and 0.77 m for SSP1-2.6 and
 279 SSP5-8.5 scenarios for 2000–2100, respectively) and Y the time period in years ($Y = 100$ years). The equivalent years
 280 of SLR recession that may be theoretically offset is then calculated by dividing the volumetric changes ΔV by Q_{offset} .

281 *Orbital wave velocities at the depth of closure*

282 Orbital wave velocities (U_{rms}) at the *DoC* for each of the three sites were estimated to assess sediment transport
 283 potential at these depths from the historical ERA5 wave reanalysis between 1970 and 2020. The wave orbital
 284 velocity can be estimated from random waves (assuming a JONSWAP spectrum) by an explicit solution defined by⁵⁵:

$$U_{rms} = \frac{0.25H_s}{T_n(1 + At^2)^3}$$

$$A = [6500 + (0.56 + 15.54t)^6]^{\frac{1}{6}}$$

$$T_n = \left(\frac{Z_{\text{DoC}}}{g} \right)^{\frac{1}{2}}$$

$$t = \frac{T_n}{T_z}$$

285 where Z_{DoC} is the seabed depth corresponding to the long-term DoC (Narrabeen = -14.3 m, Perranporth = -20.2 m, La
286 Misión = -18.2 m), H_s the significant wave height (from ERA5 reanalysis) and T_z the zero-crossing wave period. T_z is
287 calculated from the ERA5 peak wave period T_p using the spectral approximation $T_z \approx 0.78T_p$. The typical threshold of
288 motion for shoreface sediment resulting from wave orbitals at the seabed is estimated based on a characteristic
289 wave period of 10s and shoreface sediment in the range $D_{50} = 0.2\text{-}0.7$ mm (refer Figure 19 in ⁵⁶).

290 **Data Availability**

291 The data that support the findings of this study are available for download at
292 <https://doi.org/10.5281/zenodo.5748645>. Narrabeen-Collaroy survey program data is available at
293 <http://narrabeen.wrl.unsw.edu.au/>.

294 **Code Availability**

295 The code to analyse and plot the survey data in this study (written in MATLAB) is available upon request from the
296 corresponding author.

297 **Acknowledgements**

298 This study was supported by the Australian Research Council (Grant #DP150101339), the UK Natural Environment
299 Research Council (Grant NE/M004996/1; BLUE-coast project), CONACyT (CB-2014-238765 and INFR-2013-011005)
300 and the UC-MEXUS CN-18-179 project. Narrabeen survey data was collected with the support of UNSW Aviation
301 (Airborne Lidar) and the NSW Department of Planning, Industry and Environment (bathymetric data). Perranporth
302 survey data was collected thanks to the efforts of numerous generations of PhD students and researchers from the
303 Coastal Processes Research Group, University of Plymouth. La Misión data was collected thanks to the support of the
304 Coastal Morphodynamics Research Group, Universidad Autónoma de Baja California. The authors would like to
305 acknowledge traditional owners on whose lands the research was undertaken.

306 **Author Contributions**

307 M.D.H and G.M. conceptualized the study and led the writing of the manuscript. M.D.H. led the survey data
308 collection at Narrabeen and undertook the data analysis at Narrabeen and La Misión. G.M., N.V. and T.S. led the
309 survey data collection and analyses at Perranporth. A.R.A-A led the survey data collection and analysis at La Misión.
310 All authors contributed to the writing of the manuscript.

311 **References**

- 312 1. Fox-Kemper, B. *et al.* Ocean, Cryosphere and Sea Level Change. in *Climate Change 2021: The Physical Science*
313 *Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on*
314 *Climate Change* (eds. Masson-Delmotte, V. et al.) (Cambridge University Press, 2021).
- 315 2. Bruun, P. Sea-Level Rise as a Cause of Shore Erosion. *Journal of the Waterways and Harbors Division* **88**,
316 (1962).

- 317 3. Vousdoukas, M. I. *et al.* Sandy coastlines under threat of erosion. *Nature Climate Change* **10**, 260–263 (2020).
- 318 4. Meucci, A., Young, I. R., Hemer, M., Kirezci, E. & Ranasinghe, R. Projected 21st century changes in extreme
319 wind-wave events. *Science Advances* **6**, 1–10 (2020).
- 320 5. Vitousek, S., Barnard, P. L., Limber, P., Erikson, L. & Cole, B. A model integrating longshore and cross-shore
321 processes for predicting long-term shoreline response to climate change. *Journal of Geophysical Research:*
322 *Earth Surface* **122**, 782–806 (2017).
- 323 6. D’Anna, M., Idier, D., Castelle, B., Vitousek, S. & le Cozannet, G. Reinterpreting the Bruun rule in the context
324 of equilibrium shoreline models. *Journal of Marine Science and Engineering* **9**, (2021).
- 325 7. Kinsela, M. A., Daley, M. J. A. & Cowell, P. J. Origins of Holocene coastal strandplains in Southeast Australia:
326 Shoreface sand supply driven by disequilibrium morphology. *Marine Geology* **374**, 14–30 (2016).
- 327 8. Cowell, P. J., Thom, B. G., Jones, R. A., Everts, C. H. & Simanovic, D. Management of uncertainty in predicting
328 climate-change impacts on beaches. *Journal of Coastal Research* **22**, 232–245 (2006).
- 329 9. Aagaard, T. & Hughes, M. G. Equilibrium shoreface profiles: A sediment transport approach. *Marine Geology*
330 **390**, 321–330 (2017).
- 331 10. Cooper, J. A. G. & Pilkey, O. H. Sea-level rise and shoreline retreat: Time to abandon the Bruun Rule. *Global*
332 *and Planetary Change* **43**, 157–171 (2004).
- 333 11. Cooper, J. A. G. *et al.* Sandy beaches can survive sea-level rise. *Nature Climate Change* **10**, 993–995 (2020).
- 334 12. Wainwright, D. J. *et al.* Moving from deterministic towards probabilistic coastal hazard and risk assessment:
335 Development of a modelling framework and application to Narrabeen Beach, New South Wales, Australia.
336 *Coastal Engineering* **96**, 92–99 (2015).
- 337 13. Athanasiou, P. *et al.* Global distribution of nearshore slopes with implications for coastal retreat. *Earth System*
338 *Science Data Discussions* 1–29 (2019).
- 339 14. Dean, R. G. & Houston, J. R. Determining shoreline response to sea level rise. *Coastal Engineering* **114**, 1–8
340 (2016).
- 341 15. McCarroll, R. J. *et al.* A rules-based shoreface translation and sediment budgeting tool for estimating coastal
342 change: ShoreTrans. *Marine Geology* **435**, 106466 (2021).
- 343 16. Rosati, J. D. Concepts in sediment budgets. *Journal of Coastal Research* **21**, 307–322 (2005).
- 344 17. Castelle, B., Bujan, S., Ferreira, S. & Dodet, G. Foredune morphological changes and beach recovery from the
345 extreme 2013/2014 winter at a high-energy sandy coast. *Marine Geology* **385**, 41–55 (2017).
- 346 18. Masselink, G. *et al.* Extreme wave activity during 2013/2014 winter and morphological impacts along the
347 Atlantic coast of Europe. *Geophysical Research Letters* **43**, 2135–2143 (2016).
- 348 19. Harley, M. D. *et al.* Extreme coastal erosion enhanced by anomalous extratropical storm wave direction.
349 *Scientific Reports* 1–9 (2017).
- 350 20. Udo, K., Ranasinghe, R. & Takeda, Y. An assessment of measured and computed depth of closure around
351 Japan. *Scientific Reports* **10**, 1–8 (2020).
- 352 21. Hallermeier, R. J. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering* **4**,
353 253–277 (1981).
- 354 22. Valiente, N. G., Masselink, G., Scott, T., Conley, D. & McCarroll, R. J. Role of waves and tides on depth of
355 closure and potential for headland bypassing. *Marine Geology* **407**, 60–75 (2019).
- 356 23. Cowell, P. J., Roy, P. S. & Jones, R. A. Simulation of large-scale coastal change using a morphological behaviour
357 model. *Marine Geology* **126**, 45–61 (1995).

- 358 24. Thom, B. G. Transgressive and regressive stratigraphies of coastal sand barriers in southeast Australia. *Marine*
359 *Geology* **56**, 137–158 (1984).
- 360 25. Oliver, T. S. N. *et al.* Holocene evolution of the wave-dominated embayed Moruya coastline, southeastern
361 Australia: Sediment sources, transport rates and alongshore interconnectivity. *Quaternary Science Reviews*
362 **247**, 106566 (2020).
- 363 26. Dillenburg, S. & Hesp, P. A. *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*. (Springer-
364 Verlag Berlin Heidelberg, 2009).
- 365 27. Beets, D. J. & van der Spek, A. J. F. The Holocene evolution of the barrier and the back-barrier basins of
366 Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and
367 sediment supply. *Geologie en Mijnbouw/Netherlands Journal of Geosciences* **79**, 3–16 (2000).
- 368 28. Stive, M. J. F. & de Vriend, H. J. Modelling shoreface profile evolution. *Marine Geology* **126**, 235–248 (1995).
- 369 29. Anthony, E. J. & Aagaard, T. The lower shoreface: Morphodynamics and sediment connectivity with the upper
370 shoreface and beach. *Earth-Science Reviews* **210**, 103334 (2020).
- 371 30. Cowell, P. J. *et al.* Shoreface Sand Supply to Beaches. in *Proceedings 27th International Conference on Coastal*
372 *Engineering* 2495–2508 (2000).
- 373 31. Stive, M. J. F., Roelvink, D. J. A. & de Vriend, H. J. Large-scale coastal evolution concept. The Dutch coast.
374 Paper No. 9. *Proceedings of the Coastal Engineering Conference* **2**, 1962–1974 (1991).
- 375 32. Valiente, N. G., McCarroll, R. J., Masselink, G., Scott, T. & Wiggins, M. Multi-annual embayment sediment
376 dynamics involving headland bypassing and sediment exchange across the depth of closure. *Geomorphology*
377 **343**, 48–64 (2019).
- 378 33. Silva, A. P. da *et al.* Headland bypassing timescales: Processes and driving forces. *Science of the Total*
379 *Environment* **793**, 148591 (2021).
- 380 34. Fruergaard, M., Andersen, T. J., Johannessen, P. N., Nielsen, L. H. & Pejrup, M. Major coastal impact induced
381 by a 1000-year storm event. *Scientific Reports* **3**, 1–7 (2013).
- 382 35. Turner, I. L. *et al.* A multi-decade dataset of monthly beach profile surveys and inshore wave forcing at
383 Narrabeen, Australia. *Scientific Data* **3**, (2016).
- 384 36. Valiente, N. G. *et al.* Nearshore sediment pathways and potential sediment budgets in embayed settings over
385 a multi-annual timescale. *Marine Geology* **427**, 106270 (2020).
- 386 37. Mortlock, T. R., Goodwin, I. D., McAneney, J. K. & Roche, K. The June 2016 Australian East Coast Low:
387 Importance of wave direction for coastal erosion assessment. *Water* **9**, 1–22 (2017).
- 388 38. Albani, A. D., Rickwood, P. C., Quilty, P. G. & Tayton, J. W. The morphology and late Quaternary
389 paleogeomorphology of the continental shelf off Sydney, NSW. *Australian Journal of Earth Sciences* **62**, 681–
390 694 (2015).
- 391 39. de Schipper, M. A., Ludka, B. C., Raubenheimer, B., Luijendijk, A. P. & Schlacher, T. A. Beach nourishment has
392 complex implications for the future of sandy shores. *Nature Reviews Earth and Environment* **2**, 70–84 (2021).
- 393 40. Dayton, P. K., Tegner, M. J., Seymour, R. J. & Parnell, P. E. Unusual County Marine Erosion in San Diego from a
394 Single Storm. *Estuarine, Coastal and Shelf Science* **29**, 151–160 (1989).
- 395 41. Watson, P. J. Updated Mean Sea-Level Analysis: Australia. *Journal of Coastal Research* **36**, 915–931 (2020).
- 396 42. Hamon-Kerivel, K., Cooper, A., Jackson, D., Sedrati, M. & Guisado Pintado, E. Shoreface mesoscale
397 morphodynamics: A review. *Earth-Science Reviews* **209**, (2020).
- 398 43. Mayer, L. *et al.* The Nippon Foundation-GEBCO seabed 2030 project: The quest to see the world's oceans
399 completely mapped by 2030. *Geosciences* **8**, (2018).

- 400 44. Linklater, M. *et al.* Techniques for classifying seabed morphology and composition on a subtropical-
401 temperate continental shelf. *Geosciences (Switzerland)* **9**, (2019).
- 402 45. Diesing, M. *et al.* Mapping seabed sediments: Comparison of manual, geostatistical, object-based image
403 analysis and machine learning approaches. *Continental Shelf Research* **84**, 107–119 (2014).
- 404 46. Cooper, J. A. G. *et al.* Sandy barrier overstepping and preservation linked to rapid sea level rise and geological
405 setting. *Marine Geology* **382**, 80–91 (2016).
- 406 47. Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N. & Reinartz, P. Estimating satellite-derived
407 bathymetry (SDB) with the Google Earth Engine and sentinel-2. *Remote Sensing* **10**, 1–18 (2018).
- 408 48. Thom, B. G. *et al.* National sediment compartment framework for Australian coastal management. **154**, 103–
409 120 (2018).
- 410 49. Turner, I. L., Harley, M. D., Almar, R. & Bergsma, E. W. J. Satellite optical imagery in Coastal Engineering.
411 *Coastal Engineering* **167**, 103919 (2021).
- 412 50. Middleton, J. H. *et al.* Resolution and accuracy of an airborne scanning laser system for beach surveys. *Journal*
413 *of Atmospheric and Oceanic Technology* **30**, 2452–2464 (2013).
- 414 51. Turner, I. L., Harley, M. D. & Drummond, C. D. UAVs for coastal surveying. *Coastal Engineering* **114**, 19–24
415 (2016).
- 416 52. Wheaton, J. M., Brasington, J., Darby, S. E. & Sear, D. A. Accounting for uncertainty in DEMs from repeat
417 topographic surveys: Improved sediment budgets. *Earth Surface Processes and Landforms* **35**, 136–156
418 (2010).
- 419 53. Nicholls, R. J., Birkemeier, W. A. & Lee, G. Evaluation of depth of closure using data from Duck, NC, USA.
420 *Marine Geology* **148**, 179–201 (1998).
- 421 54. Hersbach, H. *et al.* The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**,
422 1999–2049 (2020).
- 423 55. Soulsby, R. L. & Smallman, J. V. *A direct method of calculating bottom orbital velocity under waves.* (HR
424 Wallingford, 1986)
- 425 56. Soulsby, R. Threshold of Motion. In *Dynamics of Marine Sands* 97–110 (Thomas Telford Publishing, 1997).
426

427

428 **Figure 1. Key sediment transport pathways under modal and extreme wave conditions on an embayed sandy**
429 **beach.** Red arrows denote sediment transport pathways during extreme storm conditions and black arrows during
430 less-energetic modal conditions. Example cross-sections at three locations in the beach compartment are: **A.** a rocky
431 headland with sandy bed above the depth of closure (DoC); **B.** a completely sandy beach system; and **C.** a rocky
432 headland with sandy bed below the depth of closure.

433

434 **Figure 2. Location and representative photos of the three study sites spanning three continents.** **a.** Global map
435 indicating location of the three study sites. Representative UAV images of the three sites are indicated for **b.**
436 Narrabeen, Australia (photo: Mitchell Harley); **c.** Perranporth, UK (photo: Tim Scott); and **d.** La Mision, Mexico
437 (photo: Amaia Ruiz de Alegría-Arzaburu).

438

439 **Figure 3. Summary of wave and entire beach variability at Narrabeen Beach, Australia.** **a.** Deep-water significant
440 wave height for Sydney (1979–2020); and **b.** during the storm-recovery sequence. **c.** Average subaerial volume
441 change from long-term surveys (1979–2020); and **d.** during the storm-recovery sequence. **e.** Overall vertical change
442 due to the storm period and **f.** during the recovery period (Depth of Closure indicated by yellow solid lines). **g.** A
443 representative cross-shore transect indicating pre-storm, post-storm and recovery morphology; and **h.** the vertical
444 change over these two periods. Shaded regions in panels **a** and **c** denote the storm-recovery sequence and triangles
445 in **b** and **d** the timing of pre-storm (blue), post-storm (red) and recovery (green) surveys. Basemap data in **e** and **f**
446 ©2022 Nearmap.

447

448 **Figure 4. Summary of wave and entire beach variability at Perranporth, UK.** **a.** Deep-water significant wave height
449 for Perranporth spanning the period of long-term beach surveys (2006–2020). **b.** Average subaerial volume change
450 from beach surveys. Triangles in **a** and **b** represent the timing of pre-storm (blue), post-storm (red) and recovery
451 (green) surveys. **c.** Overall vertical change during the storm period; and **d.** during the recovery period (Depth of
452 Closure indicated by solid yellow line). **e.** A representative cross-shore transect indicating pre-storm, post-storm and
453 recovery morphology; and **f.** the vertical change over these two periods. Note that the abrupt vertical change ($\Delta Z < -$
454 3 m) indicated during the storm period is due to frontal dune erosion caused by the storm sequence Basemap data
455 in **c** and **d** ©2022 Google (Imagery ©2022 CNES/Airbus).

456

457 **Figure 5. Summary of wave and entire beach variability at La Misión, Mexico.** **a.** Deep-water significant wave height
458 for La Misión (2015–2020) spanning the period of beach surveys. **b.** Average subaerial volume change from beach
459 surveys. Triangles in **a** and **b** denote the timing of pre-storm (blue), post-storm (red) and recovery (green) surveys. **c.**
460 Overall vertical change during the storm period; and **d.** during the recovery period (Depth of Closure indicated by
461 solid yellow line). **e.** A representative cross-shore transect indicating pre-storm, post-storm and recovery

462 morphology; and **f.** the vertical change over these two periods. Basemap data in **c** and **d** © 2022 Google (Imagery
463 ©2022 Maxar Technologies).

464




465 **Figure 6. Overall sediment budget changes due to extreme storm-recovery sequences can offset up to decades of**
466 **predicted shoreline retreat due to sea-level rise. a.** Alongshore averaged volume change (per unit metre) for
467 Narrabeen (NAR), Perranporth (PPT) and La Misi3n (MIS) beaches are indicated for the storm and recovery periods,
468 separated into subaerial (SUBAR), subaqueous (SUBAQ) and overall net change (NET). Error bars denote the 95%
469 confidence interval for calculated volume changes considering survey error. **b.** The annual rate of sediment input
470 required to theoretically offset predicted SLR recession over the 21st Century using the Bruun rule (Q_{offset}) for the
471 three sites under SSP1-2.6 and SSP5-8.5 scenarios; and **c.** the equivalent years of 21st Century SLR that may be
472 theoretically offset due to the net volumetric gains over each total period.

473

474 **Figure 7. Estimates of historical sediment transport potential at the depth of closure.** Wave orbital velocities (U_{rms})
475 at the depth of closure (DoC) are derived from ERA5 wave reanalysis (1979-2020) at each of the three study sites: **a.**
476 Narrabeen, Australia; **b.** Perranporth, United Kingdom; and **c.** La Misi3n, Mexico. Shaded regions denote the storm-
477 recovery sequences at the three sites, with darker regions corresponding to the storm periods and lighter regions
478 the recovery periods. Coloured triangles indicate the timing of pre-storm (blue), post-storm (red) and recovery
479 (green) surveys. As an indication of potential sediment transport, the approximate critical threshold of motion for
480 typical shoreface sediment ($U \approx 0.2$ m/s) is indicated as a red dashed line.

Sediment transport pathways under extreme and modal conditions



- ① Headland bypassing
- ② Headland rip current (mega-rip)
- ③ Beach rotation (longshore transport)
- ④ Beach/dune erosion (bed return flow)
- ⑤ Onshore surf zone transport (waves/currents)
- ⑥ Onshore transport from lower shoreface (skewness)
- ⑦ Estuarine/fluviol exchange
- ⑧ Offshore transport via canyon (gravity)
- ⑨ Upwelling/downwelling transport

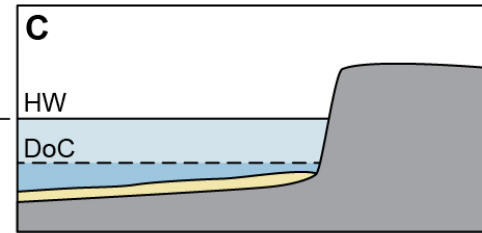
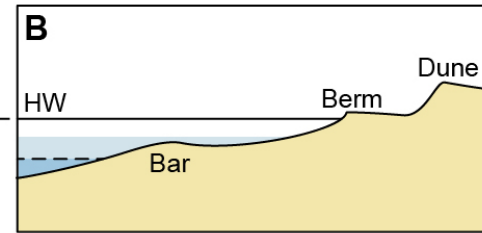
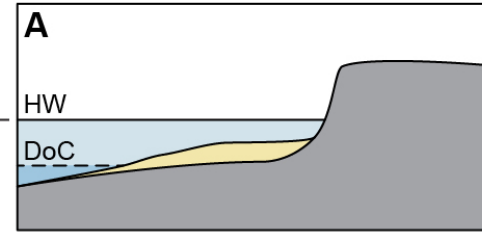
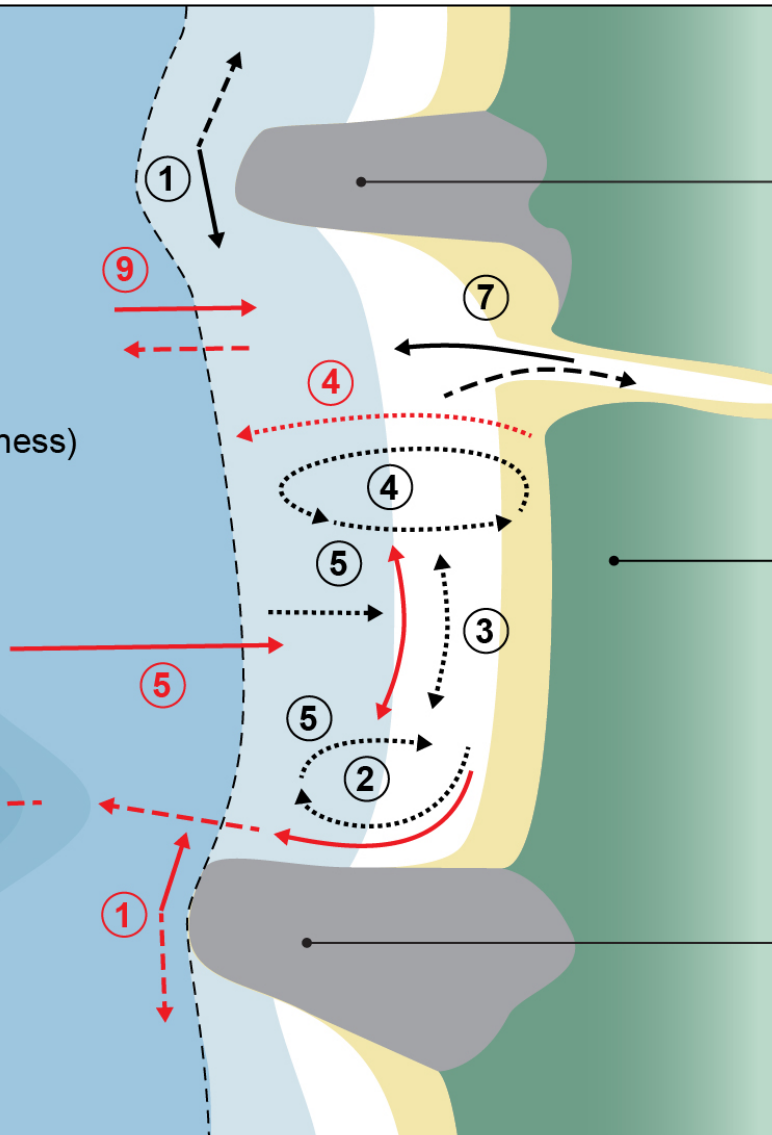
-  Depth of closure (DoC)
-  Surf zone
-  Beach/dunes

Wave forcing

-  Modal (black) / Storm (red)

Sediment pathways

-  Input (solid) / output (dashed)
-  Embayment redistribution



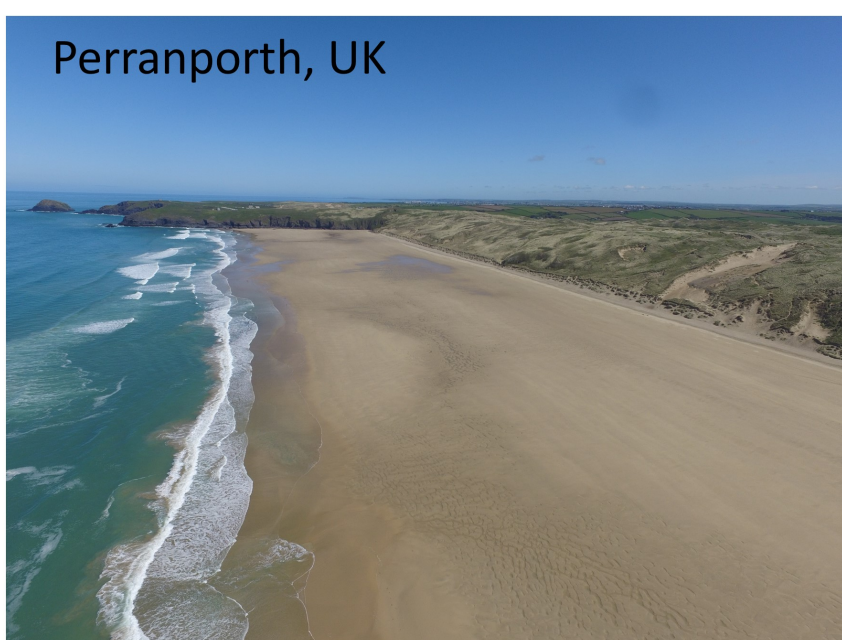
a.



b.

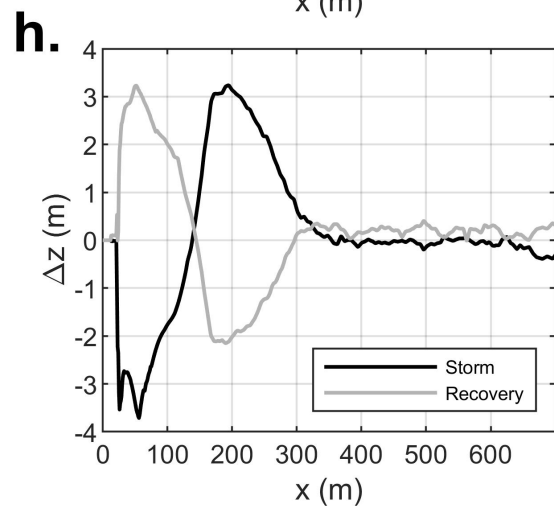
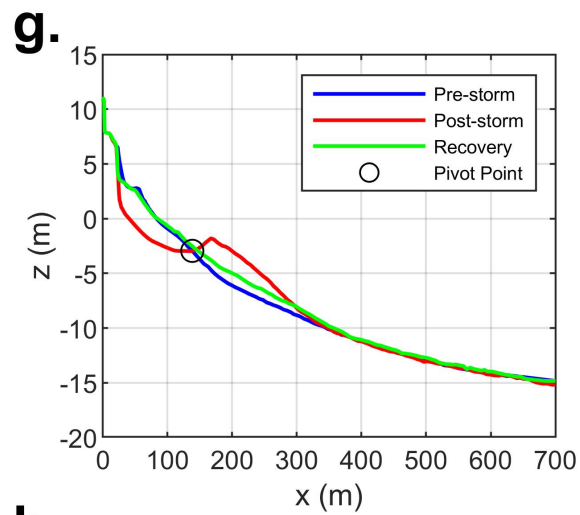
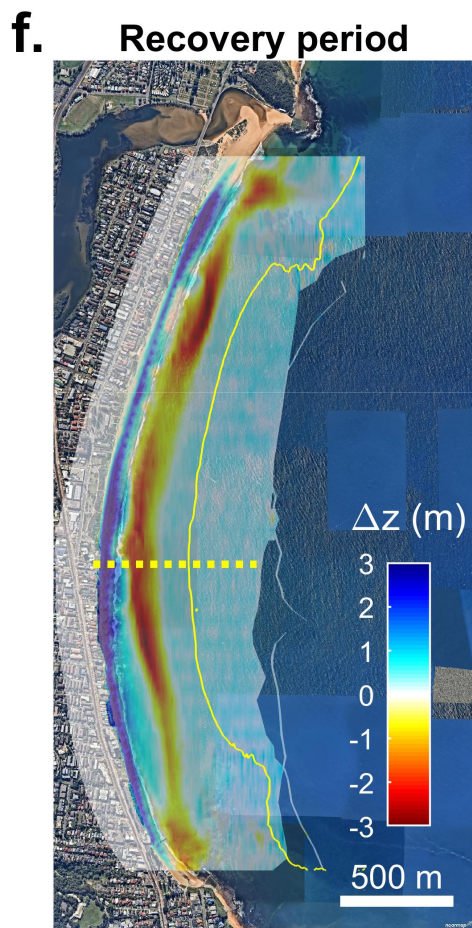
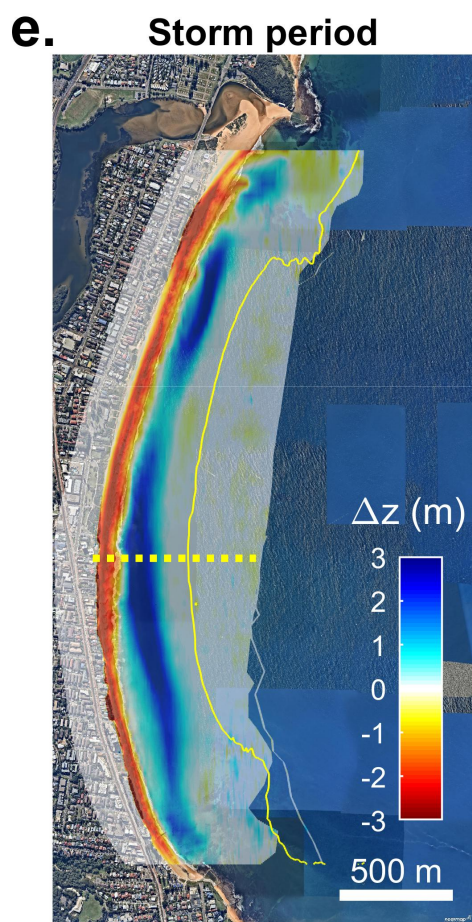
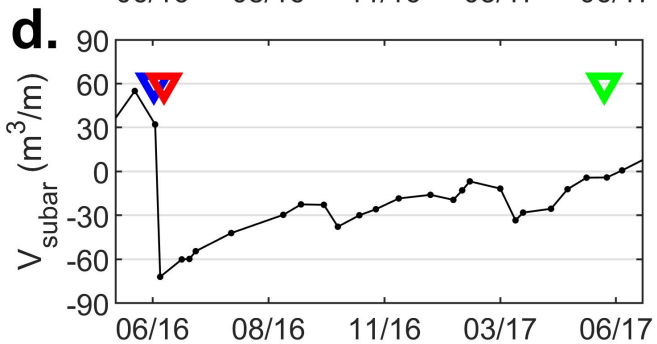
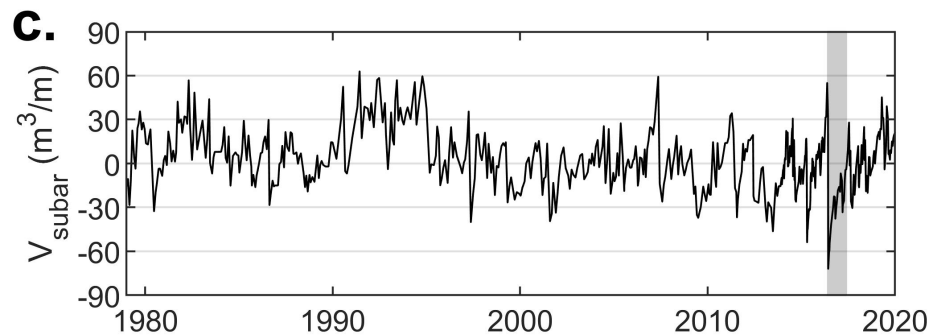
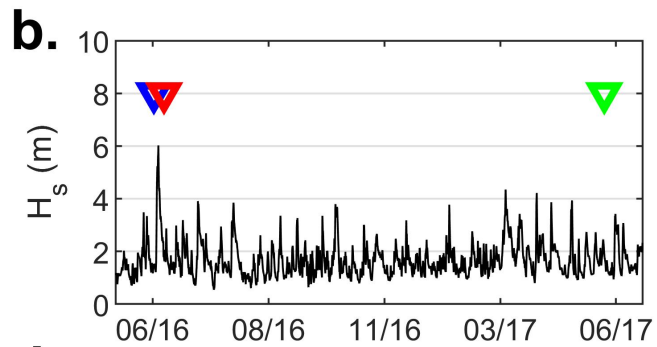
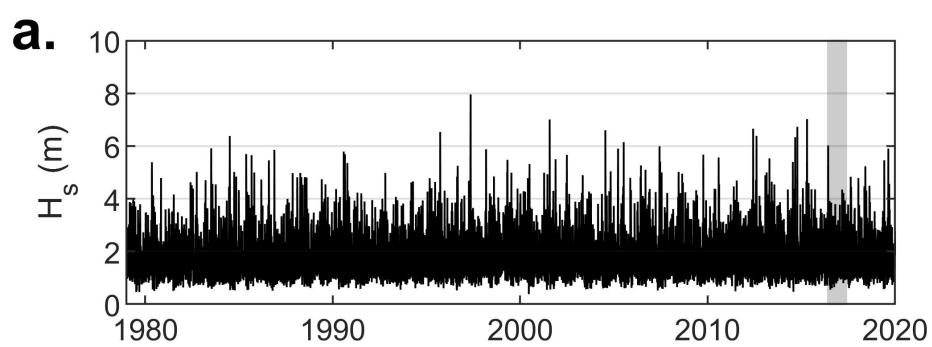


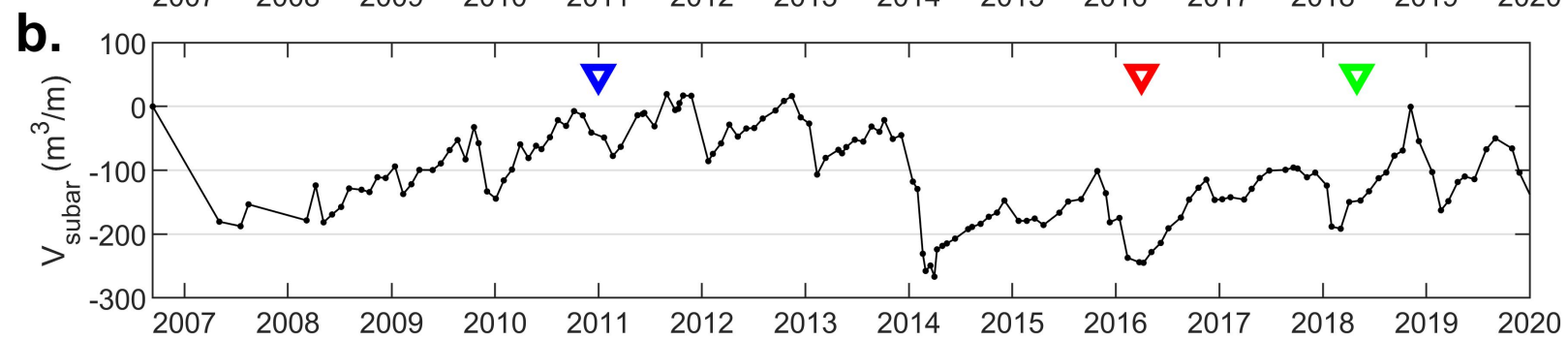
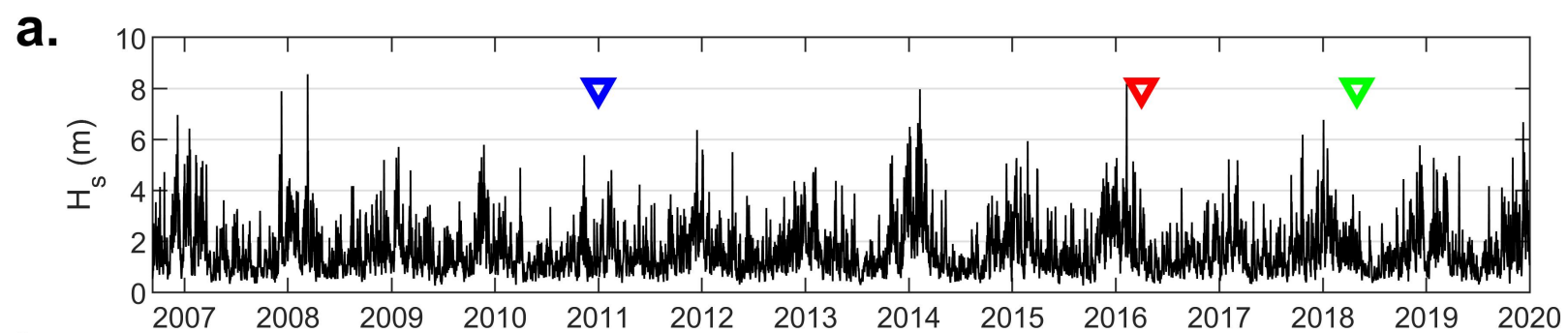
c.



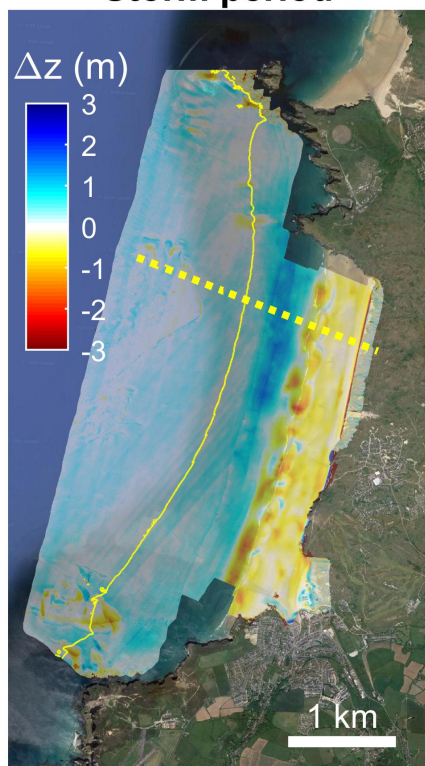
d.



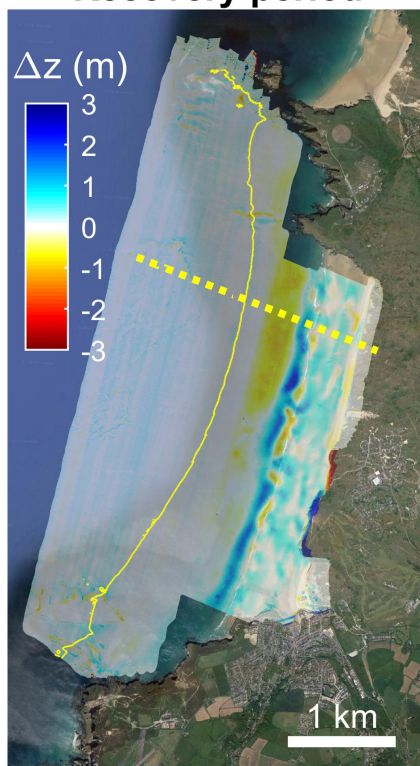




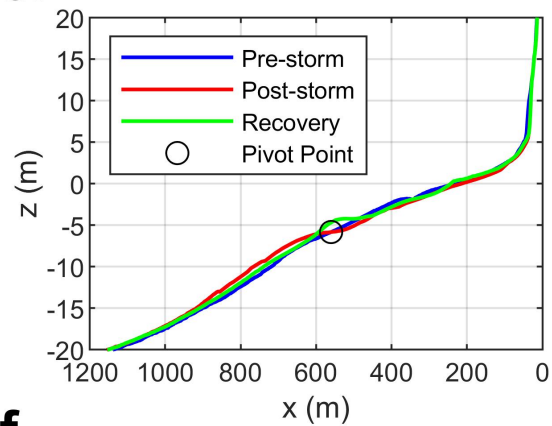
c. Storm period



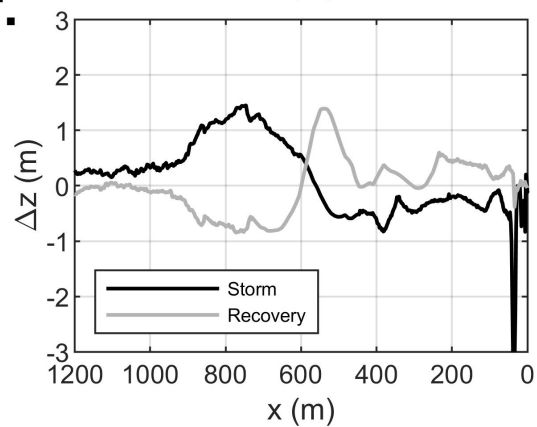
d. Recovery period

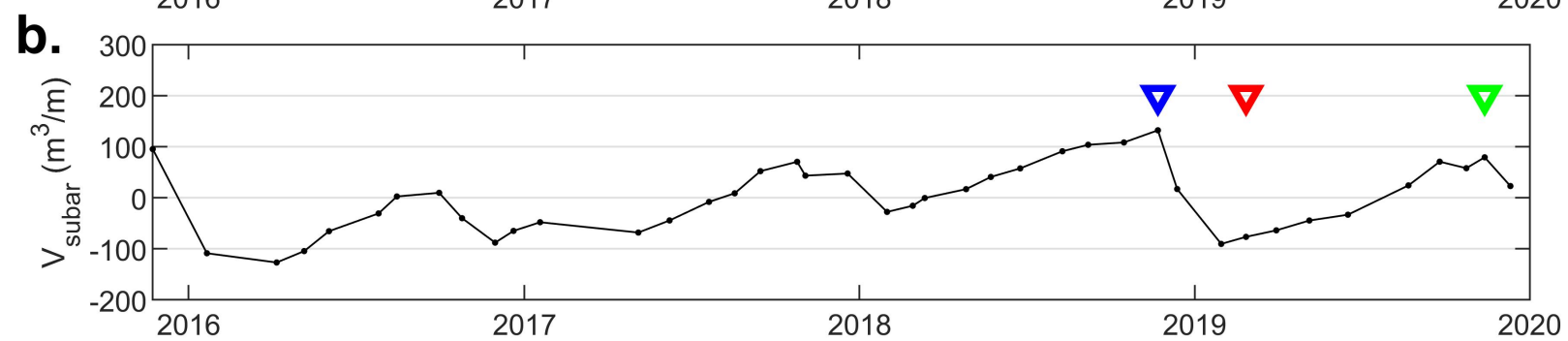
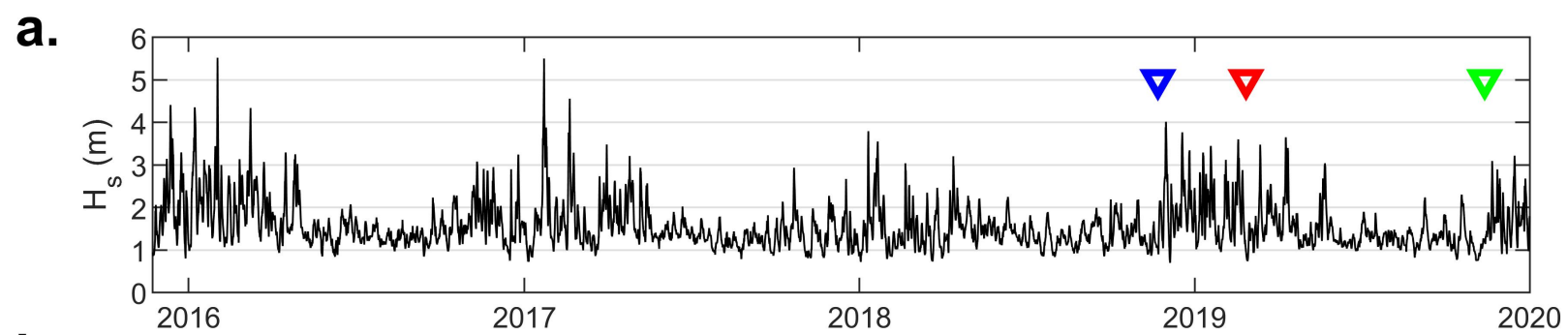


e.

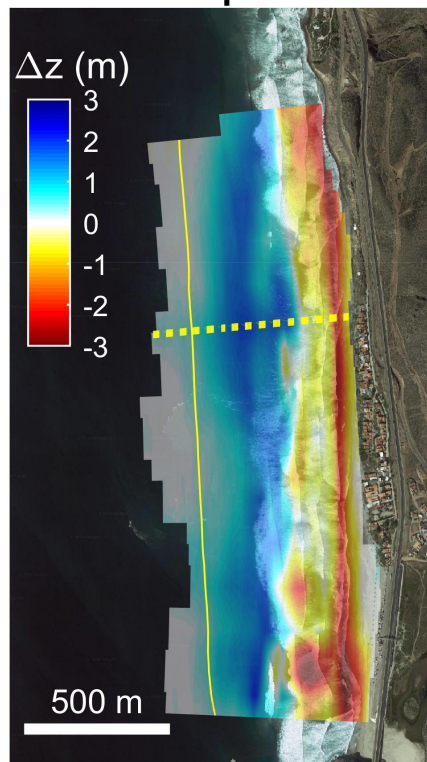


f.

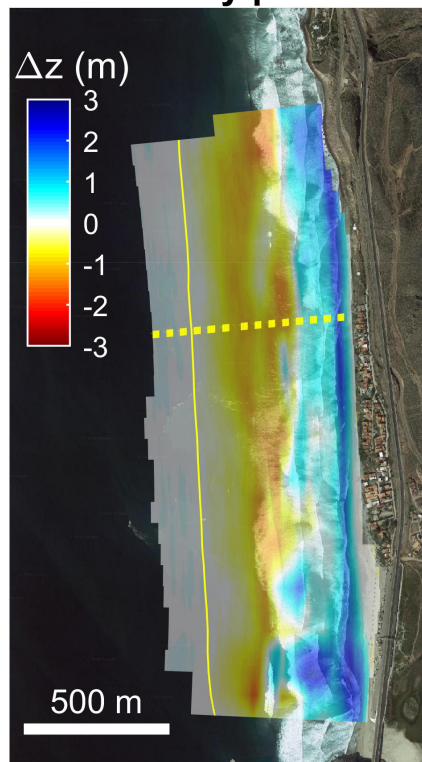




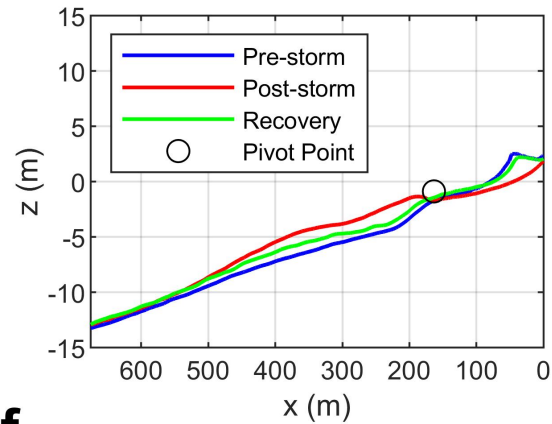
c. Storm period



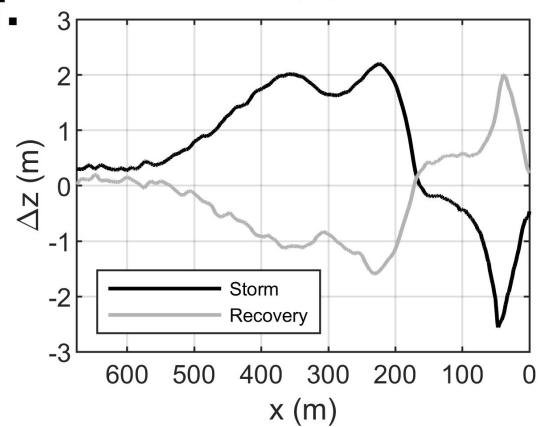
d. Recovery period

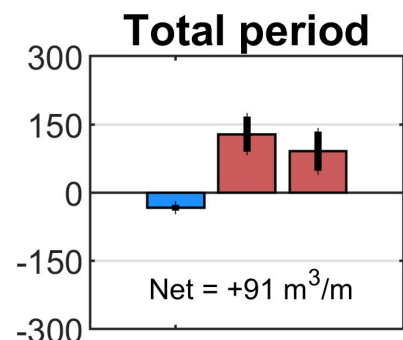
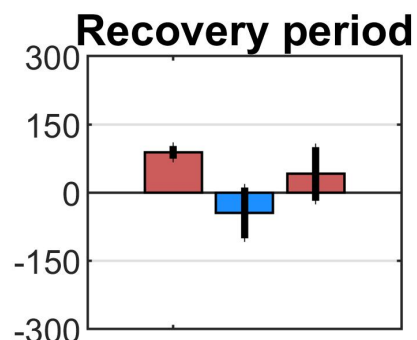
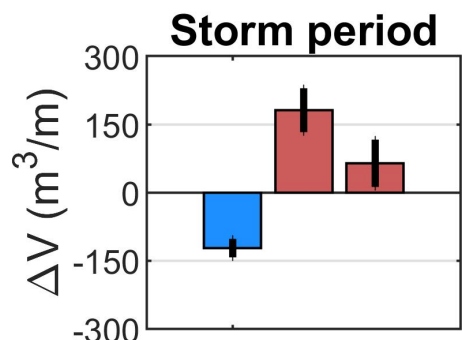
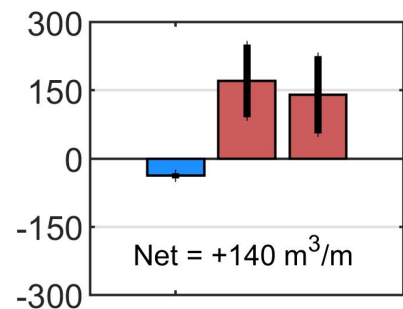
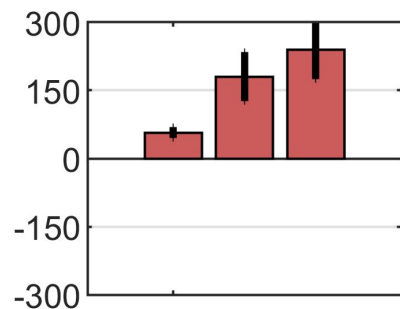
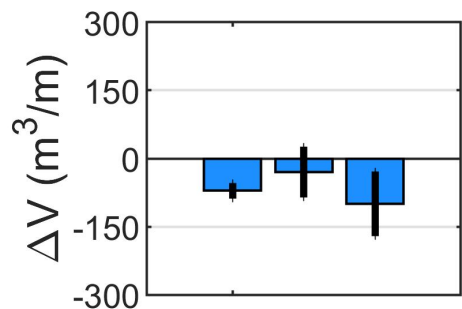
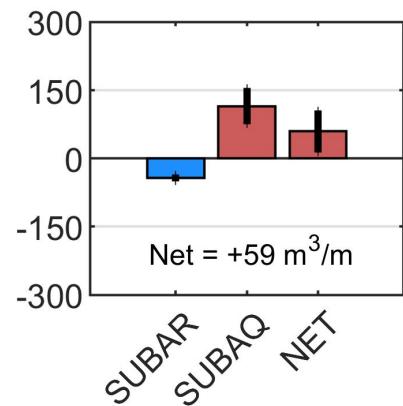
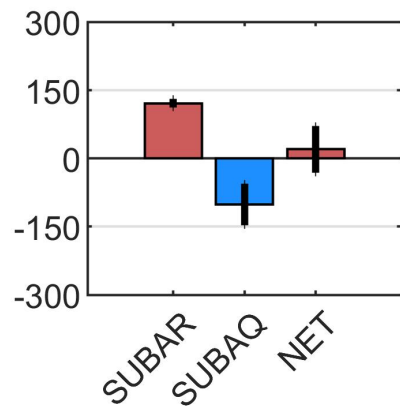
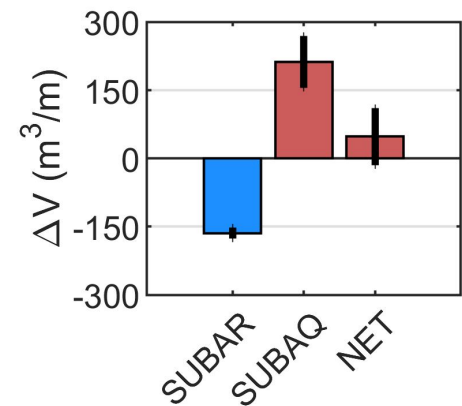
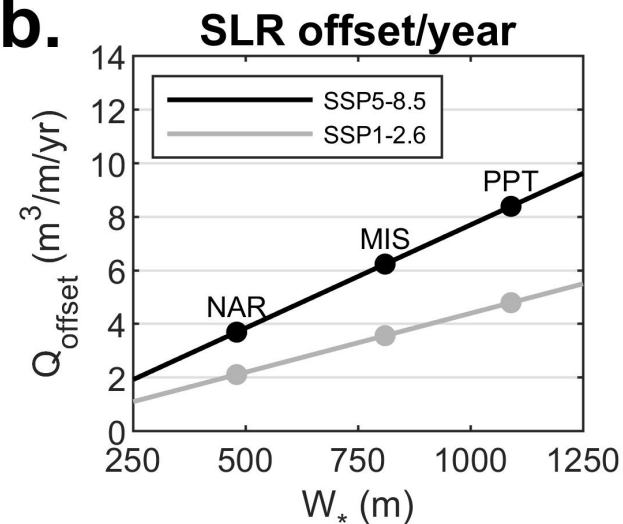
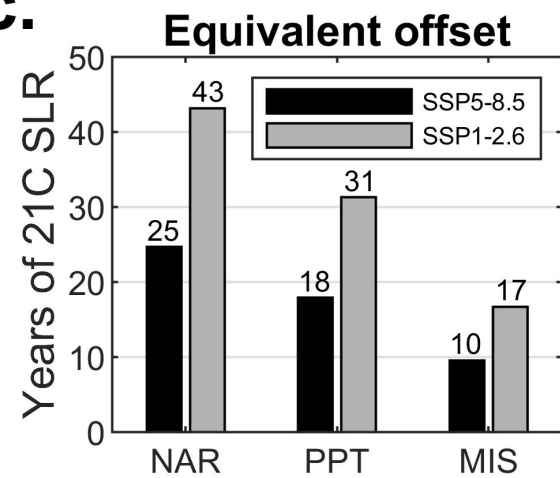


e.

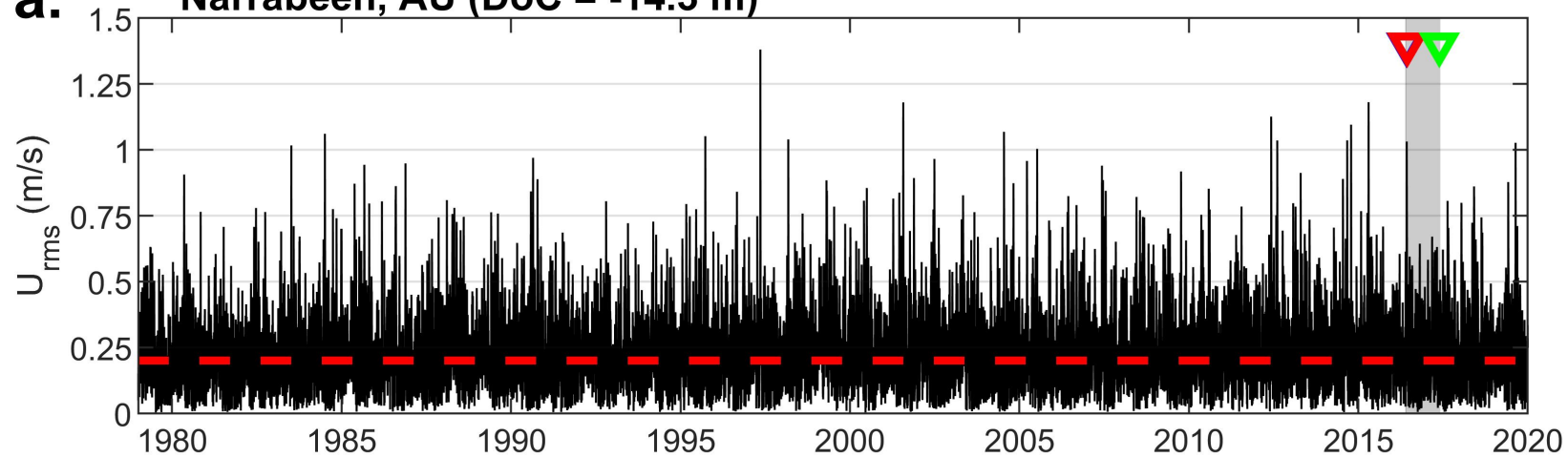


f.

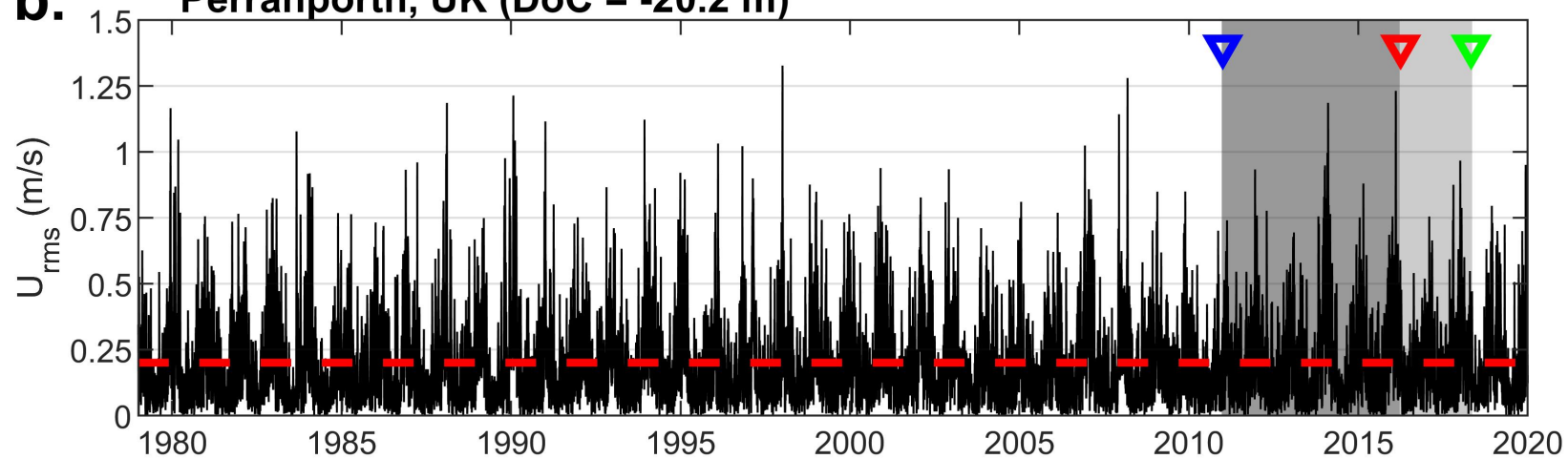


a.**NAR****PPT****MIS****b.****c.**

a. Narrabeen, AU (DoC = -14.3 m)



b. Perranporth, UK (DoC = -20.2 m)



c. La Mision, MX (DoC = -18.2 m)

