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1 **Satellite-derived shoreline detection at a high-energy meso-macrotidal beach**

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9

10 **Highlights**

- 11 • 35 years of satellite-derived shorelines at a high-energy tidal beach are analysed
- 12 • Satellite-derived shoreline proxies are compared with 10 years of field data
- 13 • A new approach using wave runup and a threshold on total water level is proposed
- 14 • The approach halves shoreline error and doubles the number of usable images

15 **Abstract**

16 Publicly available satellite imagery can now provide multi-decadal time series of shoreline data from
17 local to global scale, enabling analysis of sandy beach shoreline variability across a spectrum of
18 temporal scales. Such data can, however, be associated with large uncertainties, particularly for
19 beaches experiencing a large tidal range (> 2 m) and energetic incident waves. We use a decade of bi-
20 monthly topographic surveys at the high-energy meso-macrotidal beach of Truc Vert, southwest
21 France, and concurrent wave and water-level hindcast to investigate the uncertainties associated
22 with satellite-derived time series of the shoreline position. We show that consideration of the water
23 level and wave runup elevation are critical for accurately estimating waterline position and, in turn,
24 shoreline position. At Truc Vert, including non-tidal water level residuals (e.g. wind-driven surge) and
25 accounting for time- and elevation-varying beach slope for horizontal correction did not improve
26 satellite-derived shoreline position. A new total water level threshold is proposed to maximize the
27 number of usable images while minimizing errors. Accounting for wave runup and the new water
28 level threshold at Truc Vert, the number of usable satellite images is doubled and shoreline position
29 errors are at least halved compared to previous work at this site. Using the 1984-2019 reconstructed
30 shoreline, we also show that the satellite-derived shoreline trends and interannual variability are in
31 better agreement with field measurements. Although the approach proposed here needs to be

32 tested on other sites in different tidal/wave forcing environments with different morphological and
33 sediment characteristics, we anticipate that it will improve the temporal and spatial description of
34 shoreline change on most surf tidal beaches where accurate continuous water level and wave
35 hindcasts and/or observations are available.

36 **Keywords:** shoreline change; long-term trend; satellite; wave runup

37

39 1. Introduction

40 Understanding and predicting shoreline change along sandy coasts is of paramount importance for
41 coastal managers and policy-makers (Stive et al., 2002). Ambient (or background) long-term
42 shoreline change is an essential and sometimes dominant component in models of future shoreline
43 change due to sea-level rise (Vitousek et al., 2017; Vousdoukas et al., 2020; McCarroll et al., 2020).
44 However, shoreline variability occurs across a wide range of time scales and it can be challenging to
45 derive the ambient shoreline change unless very long data time series are available. Shorelines can
46 dramatically erode within hours as a result of storm waves (Harley et al., 2017). At the other end of
47 the spectrum, long-term, multi-decadal shoreline change is driven by various processes such as sea-
48 level rise (Ranasinghe et al., 2012) and coastal sediment supply (Carter et al., 1987). In between,
49 seasonal and interannual shoreline variability is primarily driven by changes in incident wave
50 conditions (Dodet et al., 2019); however, in sectors adjacent to tidal inlets and estuary mouths,
51 fluctuations in ebb-channel morphology can also drive shoreline variability (O'Connor et al., 2011).
52 Anthropogenic forcing, such as beach nourishments or implementation of hard structures that
53 disturb sediment pathways may also have a profound impact on shoreline variability (Turner, 2006).
54 A core issue to improve our understanding and ability to predict shoreline change is therefore to
55 monitor shoreline change at the highest possible frequency and the longest possible time scale on a
56 large range of sandy environments representative of the natural variability (Splinter et al., 2013;
57 Ibaceta et al., 2020; Toimil et al., 2020).

58 There is a wealth of coastal monitoring techniques employed to survey beach morphology and derive
59 shoreline change. These topographic surveys are often performed by means of GNSS surveys
60 (Baptista et al., 2008). Large-scale GNSS coastal monitoring programs based on widely spaced beach
61 profiles adequately distributed along 10s to 100s kilometres are scarce (Wijnberg and Terwindt,
62 1995; Ludka et al., 2019). Instead, most coastal monitoring programs focus on a single site through
63 representative profiles (e.g., Lee et al., 1998; Suanez et al., 2012; Turner et al., 2016) or detailed
64 digital elevation models (DEMs) along 100s to 1000s of metres (e.g., Stokes et al., 2015; Castelle et
65 al., 2017a), which are typically surveyed monthly or bimonthly. On similar lengths of coastline, the
66 daily shoreline proxy can be inferred from permanent video stations at reasonably low cost over
67 years to decades (e.g., Harley et al., 2011), although associated with lower accuracy.
68 Photogrammetry based on UAV images has also recently emerged as a promising tool to monitor
69 100s to 1000s metres of coast at high spatial resolution (e.g., Laporte-Fauret et al., 2019). Larger
70 scale, say 10s to 100s of kilometres, coastal monitoring programs are typically based on Lidar surveys

71 (Le Mauff et al., 2018; Nicolae Lerma et al., 2019). However, such surveys are costly and have low
72 repeat frequencies. They are therefore difficult to maintain on the long-term and do not provide
73 insight into seasonal variability.

74 Publicly available satellite imagery can now be used at no cost to provide short-term to multi-decadal
75 shoreline data from local to global scale using a variety of techniques (e.g., Garcia-Rubio et al., 2015;
76 Liu et al., 2017; Qiao et al., 2018; Douarte et al., 2018; Toure et al., 2019). Long-term (> 30 yrs) global
77 estimation of shoreline erosion and accretion were recently proposed by Luijendijk et al. (2018) and
78 Mentaschi et al. (2018). Although these studies provided unprecedented global insight into shoreline
79 change, a detailed inspection of the satellite-derived trends computed in Luijendijk et al. (2018) at
80 many high-energy and/or meso to macrotidal beaches reveals that many of these trends are not
81 supported by field data and empirical evidence. Although trends appear reliable in sectors where
82 dramatic change is observed (Luijendijk et al., 2018), the discrepancies are obvious primarily in slowly
83 evolving sectors, say less than several metres per year, and at sites with a large intra- and inter-
84 annual shoreline variability. A more accurate assessment of shoreline change rates is therefore a
85 necessary requirement to develop reliable identification of a global typology of accreting, stable and
86 eroding shores. Furthermore, these computed historical trends can be extrapolated and combined
87 with debatable sea-level-rise impact rule to conclude on shoreline position by the end of the century
88 and potential extinction of half of the world's beaches (Vousdoukas et al., 2020). In addition to
89 addressing the limitations to this approach pointed out in Cooper et al. (2020), such pioneering
90 projective work would gain in reliability by improving the historical shoreline trends, as well as
91 including the effects of potential multi-decadal variability.

92 Vos et al. (2019a) recognised issues with detecting shorelines using satellite data on dissipative
93 beaches and sites experiencing a large tidal range. After Liu et al. (2017) who showed that tidal effect
94 correction improves satellite-derived shoreline errors, Vos et al. (2019b) tested a tidal correction at a
95 meso-macrotidal site by using a time-invariant characteristic beach face slope and only using images
96 captured at higher stages of the tide. This decreased the shoreline position error by 15 m. No
97 significant improvement in their error statistics was found using slope measurements from the
98 closest survey compared to using the single time-invariant slope value. However, the effects of wave
99 runup on water level at the coast, which can cause large horizontal translation of the waterline and
100 shoreline position under moderate- to high-energy breaking waves, was not considered. Other
101 sources of errors associated with satellite-derived shorelines can also arise, such as for instance
102 through issues with geo-referencing (Schubert et al., 2017) and incorrect delineation of the
103 water/sand interface (Toure et al., 2019).

104 Overall, improving satellite-derived shoreline positions and, in turn, shoreline trends is critical to
105 more accurately discriminate accreting, stable and eroding beaches, and to reduce uncertainties in
106 future shoreline change projections in the frame of climate change, both locally and globally. In this
107 paper, we address satellite-derived shoreline evolution at the high-energy and meso-macrotidal
108 beach of Truc Vert, southwest France, using the out-of-the-box open access python-based CoastSat
109 toolkit (Vos et al., 2019a, 2019b). We explore if including astronomical tide, non-tidal water level
110 residuals, wave action and local beach slope can reduce shoreline position uncertainties, and
111 therefore lead to an improved assessment of long-term trends and interannual variability. We also
112 investigate the value of increasing the number of satellite images in the analysis. These results have
113 strong implications from the perspective of global long-term trend computations and further
114 extrapolation until the end of the century, as well as for the assessment of interannual shoreline
115 variability on beaches.

116 **2. Study area**

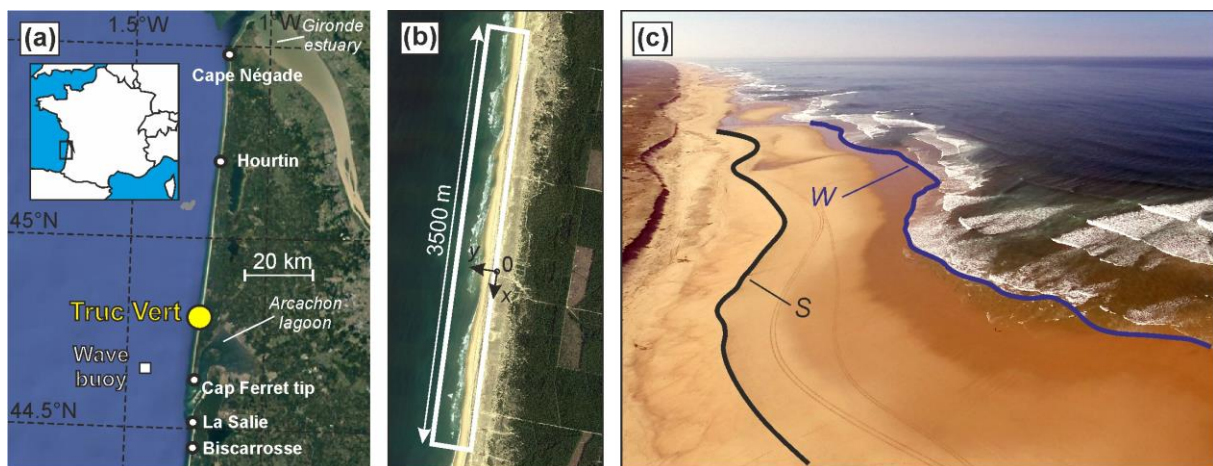
117 The study site is located in southwest France, extending c. 140 km from the Gironde estuary in the
118 north to Biscarrosse in the south, with a focus on Truc Vert beach (Figure 1a). This sandy coast
119 comprises a large beach-dune system that is only interrupted by the Arcachon lagoon inlet.

120 The wave climate at these latitudes along the Atlantic coast of Europe is generated in the North
121 Atlantic Ocean, predominantly by eastward-tracking extra-tropical cyclones. Wave conditions at Truc
122 Vert, described below, are based on a numerical wave hindcast detailed in Section 3.2. The incident
123 wave conditions are strongly seasonally modulated with the monthly-averaged significant wave
124 height H_s , peak wave period T_p and angle of wave incidence θ ranging, respectively, from 1.1 m, 8.8 s
125 and 297° in summer, to 2.4 m, 12.1 s and 287° in winter (Figure 2a–c). Thus, larger and longer waves
126 with a more western incidence occur in winter compared to summer. Winter wave activity shows a
127 strong interannual variability, with moderate winters alternating with extreme winters characterised
128 by significant spatial and temporal storm clustering (Masselink et al., 2016). High-energy winters
129 occur as a result of the intensification and southward shift of Azores high / Icelandic low dipole,
130 which is strongly correlated with the West Europe Pressure Anomaly climate index and weakly
131 associated with the North Atlantic Oscillation (Castelle et al., 2017b).

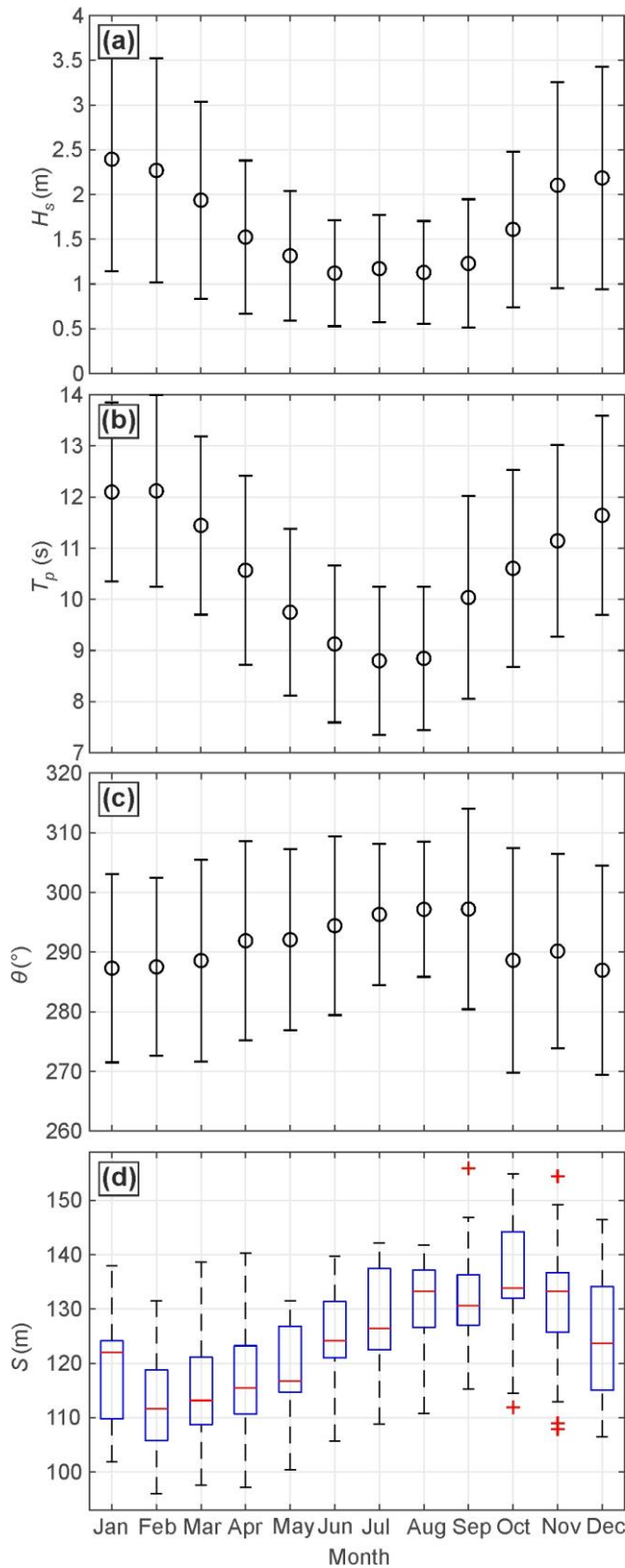
132 The coast is meso-macrotidal with an annual mean spring tidal range of 3.7 m and a largest
133 astronomical tidal range of c. 5 m (Castelle et al., 2017a). Nearshore tide-driven currents are intense
134 (> 1 m/s) in the vicinity of the Gironde estuary mouth and Arcachon tidal inlet, and are negligible ($<$
135 0.2 m/s) compared to wave-driven currents on the open coast that can well exceed 1 m/s in rip-cell
136 circulation of under energetic obliquely incident waves.

137 The beach sediment consists of medium quartz sand with a median grain size of c. 0.35 mm and a
138 large spatial variability (Gallagher et al., 2011). Except adjacent to the tidal inlet and estuary mouths,
139 beaches are morphodynamically intermediate, but with a double-bar system. The subtidal outer bar
140 is modally crescentic and a modally transverse bar-rip system characterises the intertidal inner bar
141 system. The inner and outer mean rip spacing is approximately 400 and 700 m, respectively, with
142 large spatial and temporal variability (Castelle et al., 2007; Almar et al., 2010).

143 Analysis of georeferenced aerial photographs since 1950 showed a large spatial variability of
144 shoreline change within the study area (Castelle et al., 2018). Maximum shoreline dynamics are
145 observed along the sectors adjacent to the Gironde Estuary mouth and Arcachon inlet (Figure 1a),
146 with erosion and accretion alternating on the timescale of decades. In the northern sector near Cape
147 Négade (Figure 1a), the mean erosion rate is largest at c. 5 m/yr, with a quasi-steady trend. Mean
148 erosion rate decreases southwards to 1–2 m/yr at approximately 30 km south of Hourtin (Figure 1a).
149 Further south, the coast has been relatively stable over the last 70 years along a c. 20-km long sector.
150 This sector comprises Truc Vert beach (Figure 1a), of which topographic data will be used herein to
151 compare satellite-derived shoreline dynamics.



152
153 Figure 1. (a) Location map, (b) survey region and reference frame used at Truc Vert beach and (c)
154 aerial view of Truc Vert beach taken between low and mid tide, with indication of water level (W)
155 position and visual estimate of the 1.5-m shoreline proxy S , which is the optimal shoreline proxy at
156 Truc Vert (photo: Vincent Marieu).



157

158 Figure 2. Monthly wave statistics offshore of Truc Vert for 2005–2020: (a) significant wave height H_s ;

159 (b) peak wave period T_p ; (c) angle of wave incidence θ ; and (d) cross-shore position of the

160 alongshore-averaged 1.5-m elevation shoreline proxy at Truc Vert S . Circles and vertical error bars in

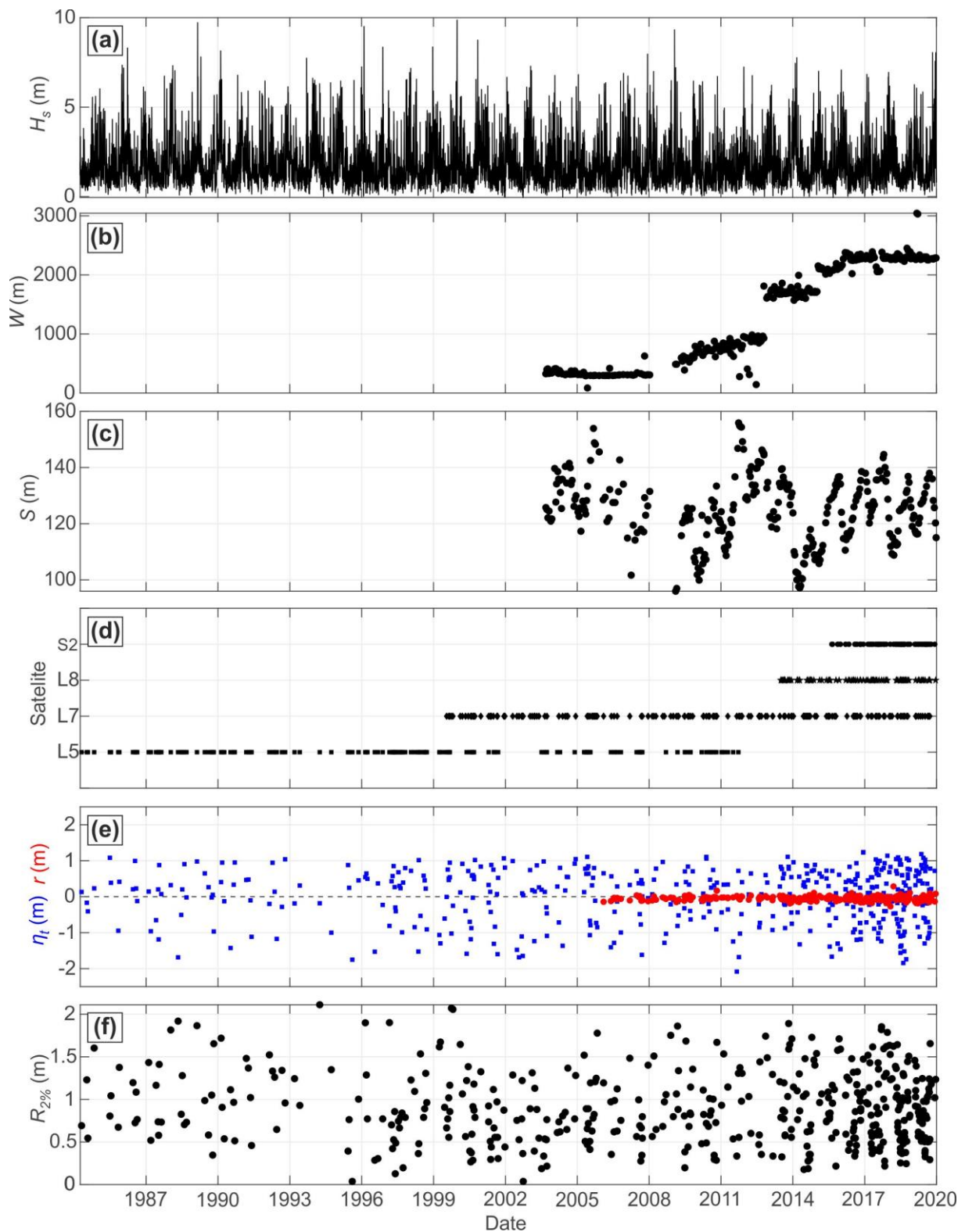
161 (a–c) indicate the monthly mean and the ± 1 monthly standard deviation, respectively. The central

162 horizontal mark in (d) indicates the median and the top and bottom edges of the blue boxes indicate
163 the 25th and 75th percentiles, respectively. Maximum whisker length extends up to 1.5 times the
164 interquartile range. Data points beyond these whiskers are considered as outliers and are displayed
165 individually as red crosses.

166 **3. Data and methods**

167 **3.1 Truc Vert beach surveys**

168 A continuous beach survey program has been operational since 2003 at Truc Vert. The resulting
169 monthly to bi-monthly beach morphology dataset is detailed and made available in Castelle et al.
170 (2020). The alongshore coverage of the surveys increased over time, exceeding 600 m in 2009 before
171 stabilizing at c. 2200 m since early 2016 (Figure 3b). Figure 3c shows the time series of 1.5-m
172 elevation shoreline proxy cross-shore position $S_{1.5m}$, which has been used as the primary shoreline
173 proxy in previous studies (e.g., Castelle et al., 2014; Splinter et al., 2014) as it best correlates with the
174 beach-dune volume (Robinet et al., 2016). It is defined as the intersection of the alongshore-
175 averaged profile with the 1.5-m AMSL elevation datum, where AMSL is obtained at Truc Vert by
176 subtracting 0.4 m from the French National Geodesic Service (NGF-IGN 69) height (Castelle et al.,
177 2020). In line with earlier work (e.g., D'Anna et al., 2020), the shoreline shows large seasonal cycles
178 with a typical amplitude of c. 30–40 m, with superimposed interannual variability of similar
179 amplitude. In the following, only the topographic data collected from 2009 onwards, which extend
180 more than 600 m alongshore, will be used for validation of local and alongshore-averaged satellite-
181 derived waterline (\bar{X}) and shoreline (\bar{S}) positions.



182

183 Figure 3. Time series of: (a) significant wave height H_s ; (b) survey alongshore coverage W ; (c) cross-
 184 shore location of the alongshore-averaged 1.5-m elevation shoreline proxy S computed from the
 185 topographic surveys; (d) usable L5, L7, L8 and S2 satellite images after automatic and visual
 186 inspection (see text for details); (e) astronomical tide η_t estimated from an harmonic analysis of

187 2006-2020 MARC hindcast, for which non-tidal residuals r were also extracted; and (f) runup
188 elevation $R_{2\%}$. All values shown in (e,f) are given at the satellite flyover time.

189 **3.2 Wave and water level data**

190 There is no continuous wave buoy measurements nearby Truc Vert covering the 1984-2019 satellite
191 image period. Instead we used a 26-year (1994–2019) time series of regional wave hindcast
192 (Boudière et al., 2013; Michaud et al., 2015) at the grid point collocated with the Candhis directional
193 wave buoy moored in c. 54 m depth southwest of Truc Vert (Figure 1a), showing excellent skill
194 against interspersed buoy measurements (see Castelle et al., 2020 for details). To further extend the
195 time series from 1994 back until the early 1980s when the first satellite images were acquired, we
196 used the 1948–2015 wave hindcast described in Masselink et al. (2016), which was validated against
197 the nearby Candhis wave buoy data in Castelle et al. (2014), although with poorer skill than with the
198 1994-2019 regional wave model.

199 A 2006-2020 coastal model hindcast of water level (Pineau Guillou, 2013) validated at Truc Vert in
200 Castelle et al. (2020) was used to estimate the water level at the coast. The astronomical tide
201 component (η_t) as well as the water level including non-tidal (atmospheric) residuals r ($\eta_{ts} = \eta_t + r$)
202 were extracted all along the coast in c. 10 m depth. A harmonic analysis of the 2006-2020 MARC
203 hindcast astronomical tide (no storm surge) was performed to extend the time series of η_t back until
204 the early 1980s (Figure 3e).

205 Breaking waves are responsible for increased water level at the shoreline (Stockdon et al., 2006). We
206 tested many set-up ζ and runup $R_{2\%}$ parametrizations, which will be discussed later in the paper.
207 Based on preliminary tests and practical considerations, we used the runup formulation of Sénéchal
208 et al. (2011), specifically calibrated at Truc Vert:

$$209 \quad R_{2\%} = 2.14 \tanh 0.4H_s \quad (1)$$

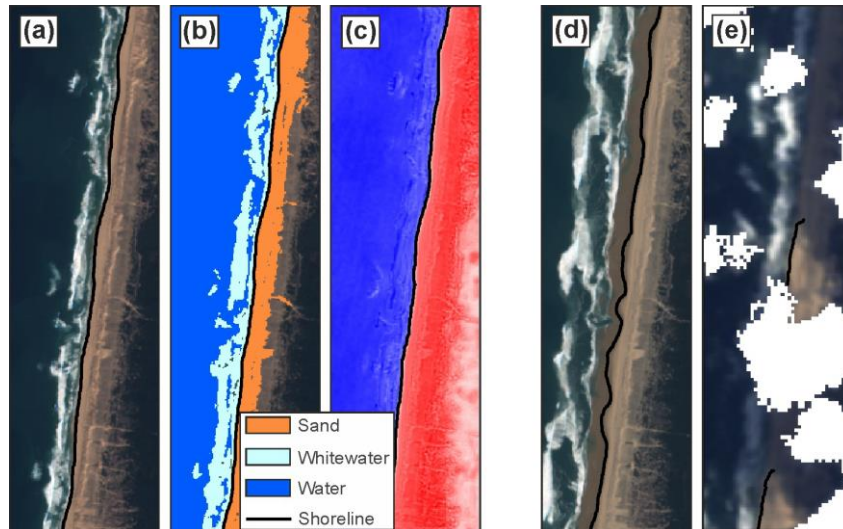
210 Contrary to many other runup parametrizations (e.g., Stockdon et al., 2006), Equation (1) implies that
211 $R_{2\%}$ can be scaled using offshore wave height alone at Truc Vert. This is in line with previous
212 observations on highly dissipative beaches (Ruessink et al., 1998; Ruggiero et al., 2001) when
213 infragravity energy dominates runup.

214 Given that we also considered disregarding any water level variation ($\eta = \eta_o = 0$), in total four
215 combinations of water level η at the coast were considered: no water level variation (η_o);
216 astronomical tide (η_t); astronomical tide + surge (η_{ts}); astronomical tide + surge + runup (η_{tsr}).

217 **3.3 Publicly available satellite images and waterline detection algorithm**

218 We used the python toolkit CoastSat (Vos et al., 2019b) which is freely-available on GitHub
219 (<https://github.com/kvos/CoastSat>). The overall approach is described in detail in Vos et al. (2019a).
220 Briefly, the toolkit allows extracting waterlines from publicly available optical satellite data through
221 Google Earth Engine. Landsat 5, 7 & 8 (L5, L7, L8, 30-m spatial resolution) and Sentinel-2 (S2, 10-m
222 spatial resolution) images are retrieved to a user-defined region of interest before pre-processing to
223 remove cloudy pixels and enhance spatial resolution. A generic waterline detection algorithm is then
224 applied, consisting of two main steps: (1) an image classification into the four classes of 'sand',
225 'water', 'white-water' and 'other' is performed based on a Neural Network classifier algorithm
226 trained on five training sites along the New South Wales coast; and (2) a sub-pixel resolution border
227 segmentation based on the Modified Normalized Difference Water Index (MNDWI), which is widely
228 used to discriminate water from land features in many applications (Xu, 2006). Instead of a global
229 threshold on the MNDWI, a refined threshold that best divides the specific 'sand' and 'water' pixels
230 by maximizing the inter-class variance is used. It provides a more stable and robust waterline
231 boundary through time (Vos et al., 2019a). A sub-pixel resolution contouring algorithm, referred to as
232 Marching Squares (Cipolletti et al., 2012), is then used to compute and map the waterline W .

233 A CoastSat region was defined at Truc Vert, with Figure 4 showing an example Sentinel-2 satellite
234 image (Figure 4a), the corresponding classified image (Figure 4b), MNDWI pixel values (Figure 4c) and
235 the resulting waterline position. Although a total of 1178 satellite images were available at Truc Vert,
236 many images were not useful. For example, more than half of the images were affected by clouds,
237 which resulted in the automatic removal of 361 images exceeding 50% of cloud cover from the
238 analysis. An additional 339 images were manually removed by visual inspection when the algorithm
239 failed to depict shoreline position for a number of reasons, including: flawed detection of the
240 water/sand limit due to a saturated intertidal domain (Figure 4d) and shadows cast by clouds
241 affecting waterline detection (Figure 4e). Recent Coastsat toolkit development now allows manual
242 adjustment of the waterline by shifting the MNDWI threshold in the MNDWI pixel intensity
243 histogram. However, at the time of using the Coastsat toolkit in the frame of this study, such
244 development was not available but will be addressed in future study. Based on a thorough visual
245 inspection of the images by the operator, a total of 478 Landsat images (including post May 2003 L7
246 images when Scan Line Corrector failed) and Sentinel images (213 since 2009) were therefore used
247 hereafter at Truc Vert representing the period 1984–2019 (Figure 3d).



248

249 Figure 4. Outputs from the CoastSat tool of Vos (2019b): (a) RGB image of Truc Vert beach from S2
 250 satellite on February 28, 2019; (b) output of image classification where each pixel is labelled as
 251 ‘sand’, ‘water’, ‘white-water’ or ‘other’; (c) pseudocolor image of the MNDWI pixel values. Examples
 252 of images manually disregarded in the analysis: (d) when the algorithm depicted the dry beach limit
 253 instead of the waterline due to a saturated intertidal domain (S2 on April 19, 2018); (e) presence of
 254 clouds and large casted shadow (L5 on February 23, 1998). In all panels, the black line indicates the
 255 waterline detected by CoastSat.

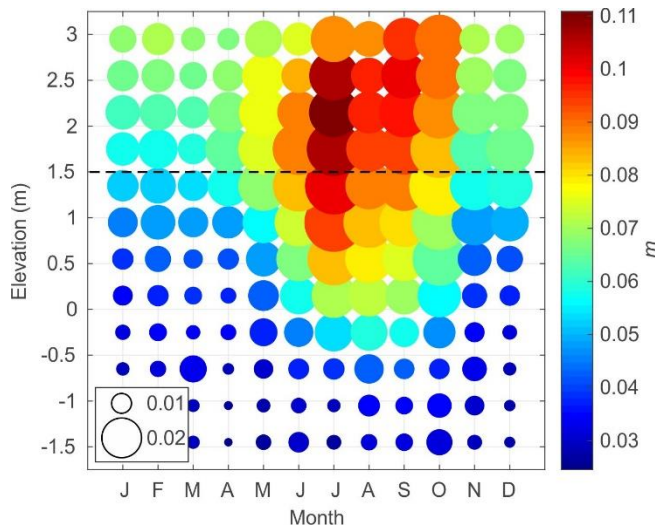
256 3.4 Shoreline position computations

257 The satellite-derived waterlines were transformed onto the local grid coordinate system. Given that
 258 satellite images were taken for a wide range of water levels (Figure 3e) and our interest is in the
 259 shoreline position S , waterline positions W were projected to 1.5 m AMSL, which is the most
 260 relevant shoreline proxy at Truc Vert as it best correlates with beach-dune volume (Robinet et al.,
 261 2016). A water-level correction was applied by translating horizontally the waterline W using a given
 262 beach slope m and the water level at the coast η at the satellite flyover time:

$$263 \quad \Delta y = \frac{\eta - 1.5}{m} \quad (2)$$

264 where Δy is the cross-shore horizontal shift, positive onshore. The four water-level elevations
 265 estimations given in Section 3.2 were tested. In addition, while a constant representative slope for
 266 Truc Vert of $m = 0.05$ was used in line with Vos et al. (2019a), a time- and elevation-dependant slope
 267 was also tested here. For the latter, the Truc Vert beach surveys were used to compute the monthly
 268 mean beach slope between the 1.5 m AMSL elevation and any elevation along the monthly-mean
 269 profile (Figure 5). Beach slope computed from the 1.5 m AMSL elevation to any elevation ranging
 270 between -1.5 m and + 3 m AMSL, with end-point slope varying from c. 0.02 to 0.11. Larger slopes are
 271 observed at the upper part of the beach during summer, and more gentle slopes during winter and

272 along the lower part of the profile. Monthly beach slope, however, shows large interannual
 273 variability (see large bubbles in Figure 5), particularly during summer at the upper part of the beach.

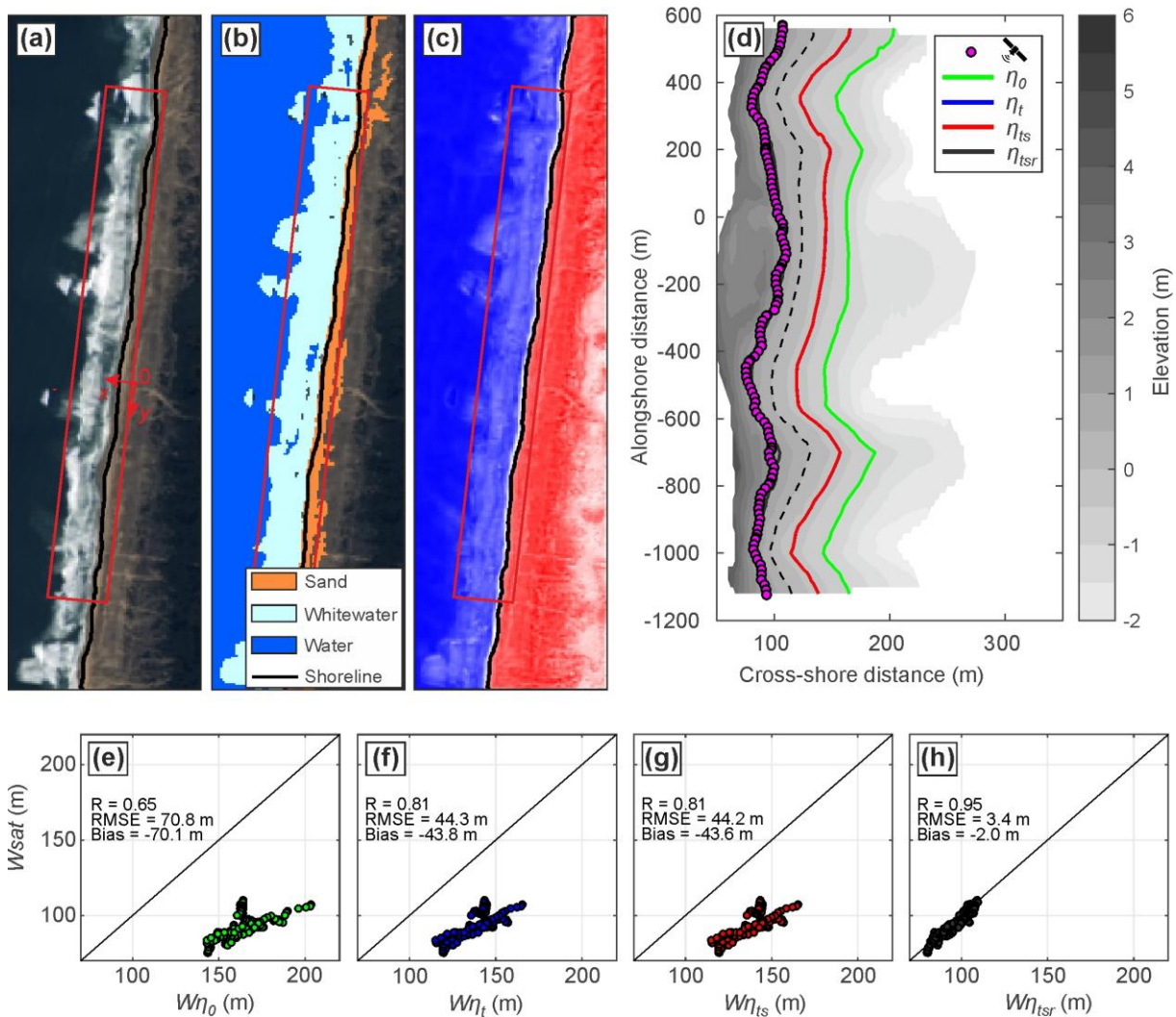


274
 275 Figure 5. Monthly- and alongshore-averaged beach slope m between a given elevation and the 1.5 m
 276 AMSL elevation, with bubble size indicating the monthly standard deviation.

277 **4. Results**

278 **4.1 Waterline detection**

279 Each satellite-derived waterline, and its cross-shore position W_{sat} , acquired since 2009 was
 280 systematically compared with the theoretical waterline (cross-shore position $W\eta$) computed using
 281 the Truc Vert beach survey performed closest to the satellite flyover date. For this, all the proxies of
 282 water level at the coast η detailed in Section 3.1 were projected on the beach survey. Figure 6 shows
 283 an example of the Landsat 8 image taken on November 17, 2014, at 10:48 AM GMT, corresponding
 284 to incident waves with $H_s = 2.8$ m near mid-high tide ($\eta_t = 0.76$ m) with negligible non-tidal residuals
 285 (< 0.01 m) and large runup ($R_{2\%} = 1.73$ m). CoastSat detects an alongshore non-uniform waterline
 286 depicting megacusp embayments enforced by the inner-bar rip channels (Figure 6a–c). This cusped
 287 morphology is also observed on the closest beach topography, which was surveyed three days later
 288 on February 20, 2019. The η_o ($\eta = 0$) elevation iso-contour is located well offshore of the satellite-
 289 derived waterline (yellow circles in Figure 6d), on average by c. 70.1 m (Figure 6e). Taking into
 290 account the astronomical tide, the η_t elevation iso-contour is located closer to the satellite-derived
 291 waterline (Figure 6d), although still well offshore by c. 43.8 m (Figure 6f). Given the negligible non-
 292 tidal residuals at the time of this L8 satellite image, the η_{ts} elevation iso-contour essentially
 293 superimposes onto that of η_t (Figure 6d,g). In contrast, including wave runup the η_{tsr} elevation iso-
 294 contour is translated landward very close to the satellite-derived waterline (Figure 6d), located
 295 onshore by c. 2.0 m with an alongshore-averaged root mean square error of 3.7 m (Figure 6h).



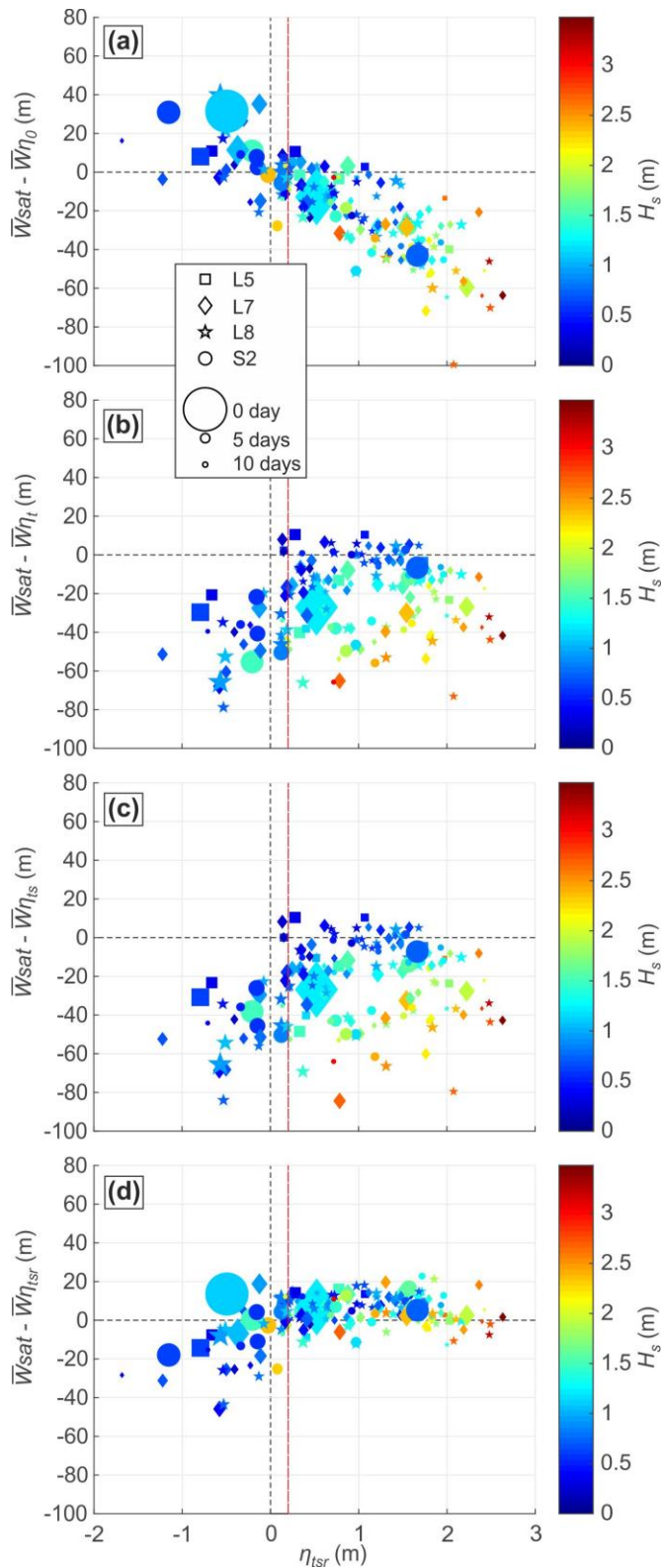
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Figure 6. (a-c) Outputs from the CoastSat tool of Vos (2019b) from L8 satellite on November 17, 2014 at 10:48 AM GMT near mid-high tide ($\eta_t = 0.76$ m) under energetic waves ($H_s = 2.8$ m) with (a) RGB image of Truc Vert beach; (b) output of image classification where each pixel is labelled as ‘sand’, ‘water’, ‘white-water’ or ‘other’; and (c) pseudocolor image of the MNDWI pixel values. In (a–c), the red box indicates survey region and reference frame used at Truc Vert beach, and the black line indicates the CoastSat waterline. (d) Truc Vert beach topographic survey on November 10, 2014, with AMSL elevation coloured, superimposed waterline points (magenta dots) detected by CoastSat in (a–c) and superimposed iso-contours of elevations: η_0 (0 AMSL), η_t (0.76 m), η_{ts} (0.76 m) and η_{tsr} (2.50 m). Note that the η_t line is hidden behind the η_{ts} line due to negligible non-tidal residual, and that the η_{tsr} line is partly hidden behind the satellite data points. The dashed black line indicates the 1.5-m elevation iso-contour (shoreline proxy at Truc Vert). Comparison of satellite-derived waterline cross-shore positions W_{sat} against cross-shore positions of iso-contours of elevation (e) η_0 , (f) η_t , (g) η_{ts} and (h) η_{tsr} with corresponding correlation (R), root-mean-square error (RMSE) and difference in means (Bias) statistics.

311 Table 1 shows the alongshore-averaged waterline cross-shore position $\bar{W}\eta$ statistics for all usable
 312 satellite images since 2009 and for each of the 4 proxies of water level η at the coast. Using all the
 313 images since 2009 ($n = 226$, left-hand column of Table 1), agreement is poor when assuming constant
 314 water level at the coast (mean sea level $\bar{W}\eta_0$, $R^2 = 0.06$, RMSE = 29.0, Bias = -14.9 m). Using
 315 astronomical tide ($\bar{W}\eta_t$) improves the agreement ($R^2 = 0.60$), while adding the atmospheric surge
 316 component ($\bar{W}\eta_{ts}$) does not provide further improvement ($R^2 = 0.59$). In all two situations, the
 317 unbiased RMSE (standard deviation STD) and Bias are however still large (STD > 20 m and Bias < -20
 318 m). Further adding wave runup to water level iso-contour greatly improves the agreement with
 319 CoastSat waterline ($\bar{W}\eta_{tsr}$, $R^2 = 0.84$, STD = 12.4 m, Bias = 3.1 m). Figure 7 further shows that, not
 320 surprisingly, errors using η_0 increase as the water level at the time of the satellite flyover deviates
 321 from MSL (Figure 7a). In contrast, using astronomical tide ($\bar{W}\eta_t$), errors are decreased for higher
 322 water levels due to steeper beach and small wave height due to smaller runup, say $\eta_{tsr} > 0$ and $H_s < 1$
 323 m (Figure 7b), which is the same further adding non-tidal residuals ($\bar{W}\eta_{ts}$, Figure 7c). Finally, further
 324 adding wave runup ($\bar{W}\eta_{tsr}$) shows that alongshore-averaged waterline positions are systematically
 325 close to that obtained with CoastSat, independent of wave height, for water levels $\eta_{mr} > 0.2$ m which
 326 is also where the break in slope occurs (Figure 7d). This is reflected in the statistics provided in the
 327 middle column of Table 1 for ($\eta_{tsr} > 0.2$ m, $n = 164$), showing that, while the coefficient of
 328 determination is slightly decreased, STD drops to 7.0 m. A positive Bias is found (7.1 m, Table 1),
 329 meaning that the satellite-derived waterline \bar{W}^{sat} is located landward of the theoretical waterline
 330 $\bar{W}\eta_{tsr}$, which will be discussed in Section 5. Interestingly, keeping only high-tide images ($\eta_t > 0.5$ m
 331 like in Vos et al., 2019a, $n = 69$), only slightly improves the results (right-hand column of Table 1), but
 332 more than halves the number of usable images. At the other end (left-hand column of Table 1), using
 333 all the images results in larger correlation ($R^2 = 0.84$) and smaller RMSE (12.8 m). However, STD is
 334 almost doubled. These results indicate that, for this study site, using η_{tsr} which includes wave runup
 335 and selecting images with $\eta_{tsr} > 0.2$ m is the optimal strategy that both minimizes alongshore-
 336 averaged waterline position error and maximizes the number of usable satellite images. Finally, it is
 337 important to note that these comparisons consider satellite images and beach surveys separated by
 338 up to 10 days (Figure 7). Given the large morphological changes occurring at Truc Vert, the errors
 339 given here must be considered as conservative.

340 Table 1. Statistics of alongshore-averaged waterline cross-shore positions $\bar{W}\eta$ for each of the 4 water
 341 elevation proxies against alongshore-averaged waterline cross-shore position \bar{W}^{sat} computed with
 342 CoastSat, using all satellite images, or selecting only those taken for $\eta_{tsr} > 0.2$ m or $\eta_t > 0.5$ m. Only
 343 satellite images for which a beach survey was performed within 10 days were considered.

	All ($n = 226$)			$\eta_{tsr} > 0.2$ m ($n = 164$)			$\eta_t > 0.5$ m ($n = 69$)		
	RMSE (STD) [m]	Bias [m]	R ²	RMSE (STD) [m]	Bias [m]	R ²	RMSE (STD) [m]	Bias [m]	R ²
$\bar{W}\eta_0$ (MSL)	29.0 (24.8)	-14.9	0.06	30.7 (17.5)	-24.2	0.05	34.0 (14.1)	-30.9	0.15
$\bar{W}\eta_t$	28.9 (20.2)	-20.7	0.60	23.4 (17.1)	-16.0	0.26	14.5 (12.0)	-8.1	0.28
$\bar{W}\eta_{ts}$	31.4 (21.1)	-23.3	0.59	26.1 (18.7)	-18.2	0.23	15.5 (12.6)	-9.1	0.24
$\bar{W}\eta_{tsr}$	12.8 (12.4)	3.1	0.84	10.0 (7.0)	7.1	0.78	10.6 (6.0)	8.7	0.80



345

346 Figure 7. Difference between alongshore-averaged iso-contour cross-shore position (\bar{W}_{η}) for
 347 elevations (a) η_0 , (b) η_t , (c) η_{ts} and (d) η_{tsr} and alongshore-averaged waterline cross-shore position
 348 computed with CoastSat \bar{W}_{sat} , positive meaning more landward satellite-derived waterline, against
 349 estimated total water level η_{tsr} . In all panels, significant wave height H_s is coloured, the vertical
 350 dashed red line indicates the $\eta_{tsr} = 0.2$ m threshold, symbol indicates the satellite and symbol size is

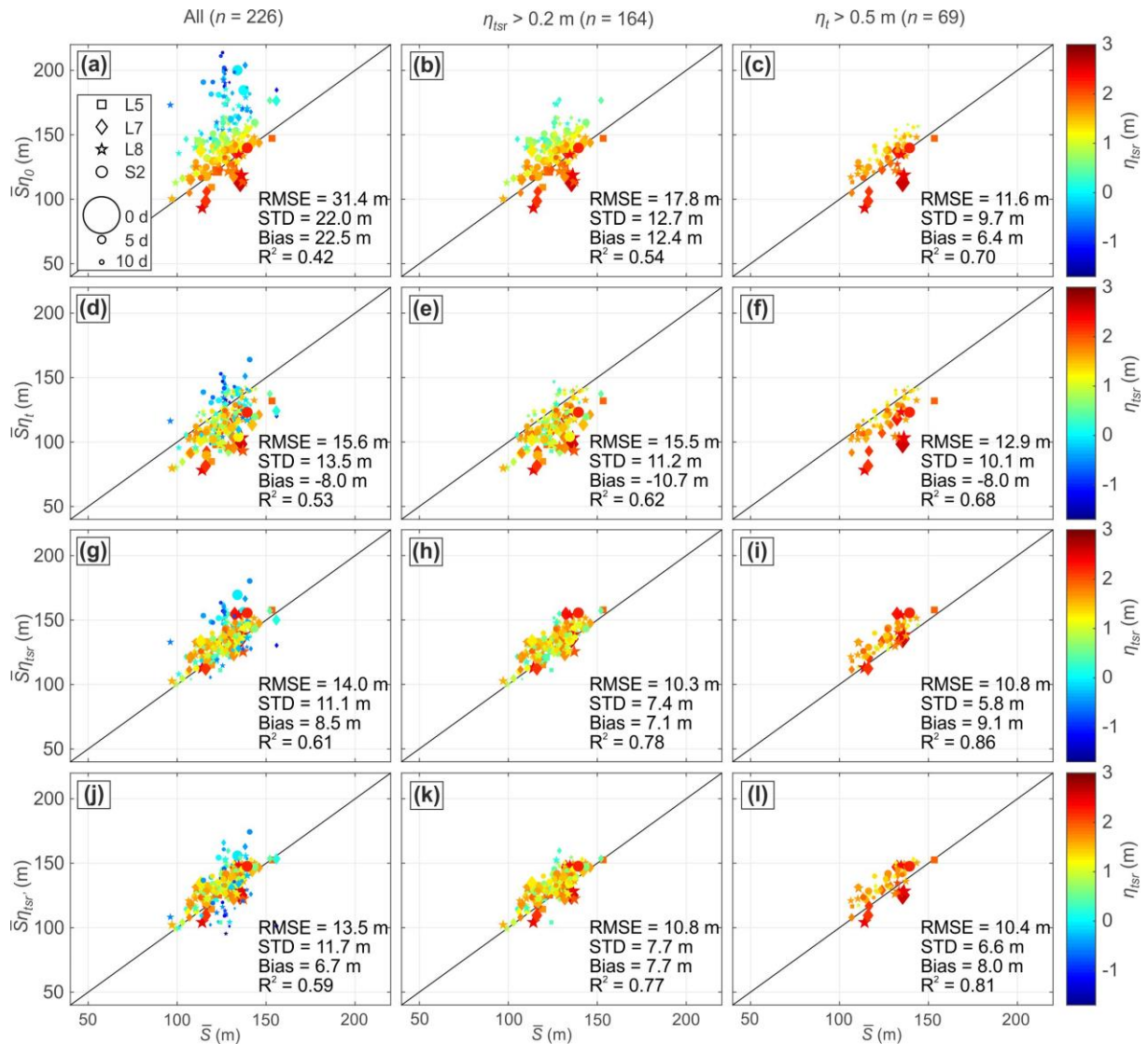
351 proportional to the duration between the satellite image and the closest Truc Vert beach
352 topographic survey used to compute iso-contours.

353 4.2 Shoreline position

354 Based on the results of the analysis on the role of water level proxies on the alongshore-averaged
355 waterline cross-shore position $\bar{W}\eta$, and to facilitate comparison with earlier work, only four satellite-
356 derived shoreline position ($S\eta$) methods are further considered by translating horizontally a given
357 waterline $W\eta$ using a given beach slope. Below we now disregard elevation η_{ts} as non-tidal residuals
358 were found to have negligible impact on waterline position at Truc Vert and address four alongshore-
359 averaged shoreline position: (1) $\bar{S}\eta_0$ ignoring tide; (2) $\bar{S}\eta_t$ with tidal correction using water level η_t
360 and a constant slope ($m = 0.05$ in Equation (2)) as in Vos et al. (2019a); (3) $\bar{S}\eta_{tsr}$ with tidal correction
361 using water level η_{tsr} (i.e. including wave runup) and a constant slope $m = 0.05$ and (4) $\bar{S}\eta_{tsr}$ with
362 tidal correction using water level η_{tsr} (i.e. including wave runup) and the time- and elevation-varying
363 monthly beach slope shown in Figure 5 feeding Equation (2). Figure 8 shows that the poorest
364 agreement with field data is found for $\bar{S}\eta_0$ (STD = 22.0 m, $R^2 = 0.42$, Figure 8a), although agreement
365 substantially improves when only considering high-tide images ($\eta_t > 0.5$ m; STD = 10.9 m, $R^2 = 0.64$,
366 Figure 8c). Surprisingly enough, using $\bar{S}\eta_t$ for high-tide images does not further improve the results
367 (Figure 8f). Although a direct comparison cannot be performed, Vos et al. (2019a) who used 74
368 satellite-derived shorelines between 2005-2018 for $\eta_t > 0.5$ m at a single transect at Truc Vert, found
369 similar results (STD = 12.7 m, $R^2 = 0.46$). In contrast, results dramatically improve for $\bar{S}\eta_{tsr}$ (STD = 5.8
370 m, $R^2 = 0.86$, Figure 8i), meaning that including runup in water level estimation at this coast is key to
371 improve the derived shoreline position. It is important to note that similar agreement is obtained
372 disregarding non-tidal residuals and only including astronomical tide and wave runup (STD = 5.6 m, R^2
373 = 0.86, not shown).

374 Results are not further improved when using a time- and elevation-varying monthly beach slope
375 $\bar{S}\eta_{tsr}$ (STD = 6.6 m, $R^2 = 0.81$, Figure 8l). This means that, in line with Vos et al. (2019a), further
376 including a presumably better description of beach slope does not necessarily improve the derived
377 shoreline position. While the best results are obtained for $\bar{S}\eta_{tsr}$ for high-tide images, importantly,
378 performance is only marginally less good by including more than twice as many images for $\eta_{tsr} > 0.2$
379 m (STD = 7.4 m, $R^2 = 0.78$ in Figure 8h). Therefore, using $\bar{S}\eta_{tsr}$ appears as the optimal approach to
380 infer shoreline position by both maximizing the number of usable images leading to improved
381 temporal resolution of the shoreline signal and minimizing spatial error associated with the shoreline
382 estimates. Importantly, a substantial positive 7.1 m bias is found, meaning that satellite-derived
383 shoreline is located too far seaward, which will be discussed in Section 5. Disregarding non-tidal

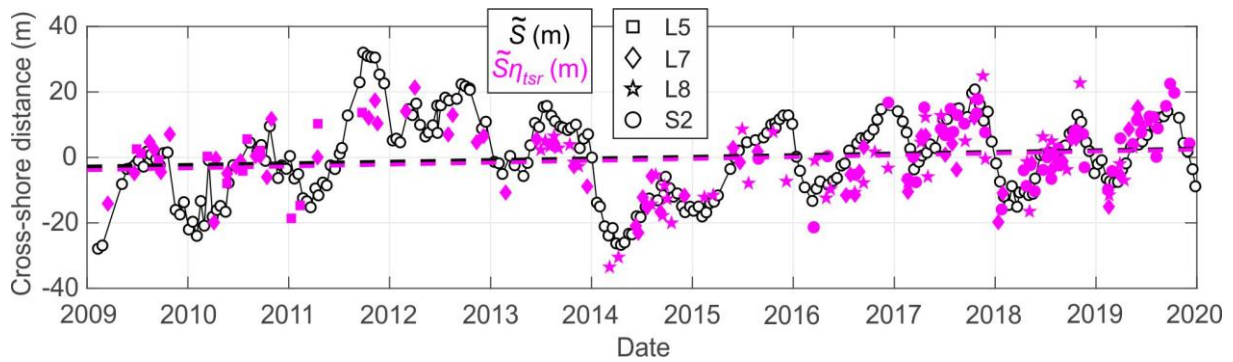
384 residuals and only considering astronomical tide and wave runup ($\bar{S}\eta_{tsr}$) gives similar results (STD =
 385 7.2 m, $R^2 = 0.78$ for $\eta_{tsr} > 0.2$ m, not shown) to $S\eta_{tsr}$. This emphasizes that astronomical tide and wave
 386 runup are key to satellite-derived shorelines, and that, at Truc Vert, non-tidal residuals can be
 387 disregarded. Finally, as per the waterline detection, all these errors are considered conservative due
 388 to the comparison window (< 10 days between the satellite image the beach survey used for
 389 comparison).



390
 391 Figure 8. Satellite-derived alongshore-averaged shoreline position against in-situ shoreline position
 392 with corresponding statistics using only satellite images for which a beach survey was performed less
 393 than 10 days before or after. A positive bias means that satellite-derived shoreline is located too far
 394 seaward. The analysis includes (left-hand panels) all usable satellite images since 2009 ($n = 226$);
 395 (middle panels) only satellite images for $\eta_{tsr} > 0.2$ m ($n = 164$); and (right-hand panels) only satellite
 396 images for $\eta_t > 0.5$ m ($n = 69$). (a–c) $\bar{S}\eta_0$, (d–f) $\bar{S}\eta_t$, (g–i) $\bar{S}\eta_{tsr}$ and (j–l) $\bar{S}\eta_{tsr}'$.

397 **4.3 Shoreline change analysis: long term trend and interannual variability**

398 Figure 9 shows the time series of alongshore-averaged shoreline position (1.5 m AMSL elevation
 399 shoreline proxy) deviation from the mean measured at Truc Vert (\tilde{S}) and that derived from satellite
 400 images $\tilde{S}_{\eta_{tsr}}$ for images with $\eta_{mr} > 0.2$ m. The satellite-derived shoreline readily reproduces the
 401 seasonal and interannual cycles at Truc Vert, despite a few outliers. The computed 2009–2019
 402 shoreline trends from measurements and satellite are +0.50 m/yr and +0.57 m/yr, respectively,
 403 therefore showing good agreement. Noteworthy, the trend computed using \tilde{S}_{η_0} ($n = 226$) and \tilde{S}_{η_t} (n
 404 = 69) is 0.81 m/yr and 0.78 m/yr, respectively, which is substantially larger, but of the same order of
 405 magnitude as that derived using $\tilde{S}_{\eta_{tsr}}$ ($n = 164$). Importantly, disregarding non-tidal residuals but
 406 keeping runup contribution, 2009-2019 shoreline trend of $\tilde{S}_{\eta_{tr}}$ is 0.63 m/yr, which is closer to that
 407 computed from the topographic surveys.

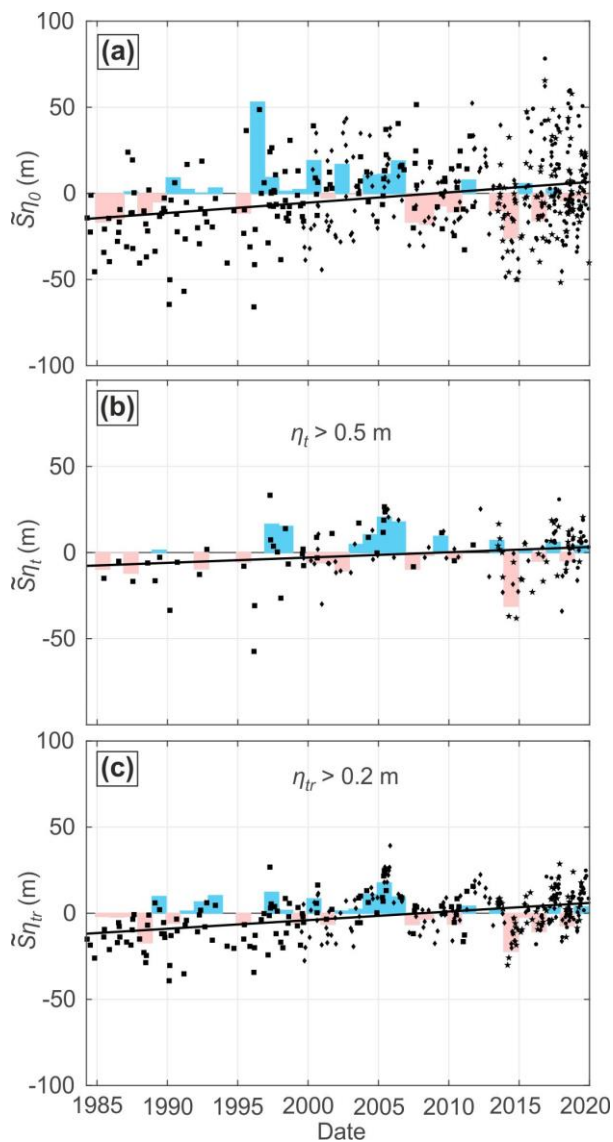


408
 409 Figure 9. Time-series of shoreline change at Truc Vert beach derived from satellite $\tilde{S}_{\eta_{tsr}}$ compared
 410 with in-situ shoreline position \tilde{S} with superimposed trends (dashed lines).

411 Figure 10 shows the time series of shoreline deviation from the mean for the entire satellite image
 412 dataset, starting from April 21, 1984. Figure 10b shows the results using our optimal approach, which
 413 is here disregarding hindcasted non-tidal residuals as they are not available prior to 2006 (and
 414 including these did not represent significant improvement anyway). The corresponding $\tilde{S}_{\eta_{tr}}$ long-
 415 term trend using images with $\eta_{tr} > 0.2$ m is 0.50 m/yr, which is very similar to that computed for the
 416 2009-2019 period (Figure 10a). The long-term trend computed with shoreline \tilde{S}_{η_0} is also similar
 417 (+0.60 m/yr), while that using \tilde{S}_{η_t} for images with $\eta_t > 0.5$ m is slightly reduced (+0.31 m/yr).

418 To emphasize interannual variability, we computed the yearly post-winter mean shoreline position
 419 from which we subtracted the long-term trend (coloured bars in Figure 10a). The number of usable
 420 satellite images increased in time (Figure 3d) from 2 in 1993 and 1994 to 49 in 2018, and also varied
 421 seasonally, ranging from 0.34 images per year in January to 1.91 images in June (related to cloud
 422 cover). Therefore, in order to maximize the number of post-winter satellite-derived shoreline
 423 positions, we systematically averaged all available shoreline data between April and July. Clearly,
 424 strong interannual variability is highlighted, with a typical amplitude of 30–40 m, and with the

425 2013/2014 winter standing out for all shoreline proxies $\tilde{S}\eta_{tr}$ (Figure 10b). Interannual cycles are
 426 more pronounced using $\tilde{S}\eta_0$ for all images, with a lot of shoreline outliers (Figure 10a). Interannual
 427 cycles for
 428 $\tilde{S}\eta_t$ and $\tilde{S}\eta_{tr}$ are more similar in patterns, although using $\tilde{S}\eta_t$ for images with $\eta_t > 0.5$ m does not
 429 provide enough post-winter data to address interannual variability prior to the 2000s due to the lack
 430 of available images (Figure 10c). Previous work showed that shoreline inter-annual variability on the
 431 open beaches of the Atlantic coast of Europe at these latitudes, and particularly at Truc Vert, is
 432 strongly affected by the WEPA index (Dodet et al., 2019). A high negative correlation ($R = -0.82$) was
 433 found between post-winter $\tilde{S}\eta_{tr}$ and winter WEPA index, while correlation drops for $\tilde{S}\eta_0$ ($R = -0.50$)
 434 and $\tilde{S}\eta_t$ ($R = -0.49$). This suggests that interannual shoreline variability can be better depicted using
 435 $\tilde{S}\eta_{tr}$ for $\eta_{tr} > 0.2$.



436
 437 Figure 10. Time-series of satellite-derived shoreline position deviation from the mean at Truc Vert
 438 beach, with the coloured bars showing the interannual variability (trend removed) in post-winter

439 shoreline position and the solid line depicting long-term trend: (a) $\tilde{S}\eta_0$ for all images; (b) $\tilde{S}\eta_t$ for
440 images with $\eta_t > 0.5$ m; (c) $\tilde{S}\eta_{tr}$ for images with $\eta_{tr} > 0.2$ m.

441 5. Discussion and conclusions

442 Our results indicate that, without having to improve the CoastSat satellite-derived waterline
443 algorithm, the estimation of shoreline position, defined as the profile intersection with a given
444 elevation datum, can be greatly improved on a meso-macrotidal high-energy sandy beach. Crucial to
445 this improvement is accounting for the wave runup. This was surprising as it is highly unlikely that
446 most satellite images were taken at maximum runup excursion. Instead it was expected that the
447 wave set-up, defined by the time-averaged water level of the waterline would be a better descriptor
448 of the shoreline position. However, a preliminary analysis showed that wave set-up only slightly
449 improved waterline detection compared with disregarding wave effects. An explanation for this is
450 that because beaches such as Truc Vert tend to remain wet after the passage of a single runup event,
451 the CoastSat algorithm picks-up the interface between the recent runup (wet) and dry sand instead
452 of the sand/water interface. This may also explain why although the variance in waterline position is
453 largely accounted for by including the wave runup component, the average position of the resulting
454 time- and space-averaged waterline is shifted landward by 7.1 m. (Table 1). Improving the waterline
455 detection for such an environment by using the mean runup instead of the 2% exceedance runup
456 ($R_{2\%}$) will need further investigation. We also tested other set-up and runup formulas, which did not
457 yield better results. For instance, the formulation used here by Sénéchal et al. (2011) resulted in a
458 substantially large inshore bias (runup overestimation) of waterline position compared to other
459 formulas, meaning that runup elevations are possibly overestimated. However, this formulation
460 provided the best variance explanation, which is why it was preferred therein. For instance, using
461 images with $\eta_{tsr} > 0.2$ m, waterline STD and R^2 are 7.0 m and 0.78 (Table 1), respectively. Results
462 worsen using the runup parametrizations proposed by Stockdon et al. (2006) for intermediate and
463 dissipative beaches, with STD = 8.8 m and $R^2 = 0.67$ for the intermediate beach parametrization, and
464 with STD = 8.7 m and $R^2 = 0.67$ for the dissipative parametrization. However, waterline estimation
465 using Stockdon et al. (2006) is still greatly improved compared with when wave contribution to water
466 level at the coast is disregarded ($\bar{W}\eta_0$ and $\bar{W}\eta_t$ in Table 1). Our new approach also allows using a
467 lower water level threshold ($\eta_{tsr} > 0.2$ m), greatly increasing the number of useable images available
468 for shoreline change analysis. This improvement is especially important for higher latitudes where
469 more frequent cloud cover significantly reduces the number of cloud-free images. However, this
470 threshold is likely site specific and does not correspond to any salient break in beach slope at Truc
471 Vert. Environmental factors controlling this threshold will need to be addressed by exploring
472 satellite-derived shoreline at other beaches where beach profiles are regularly surveyed.

473 Including the non-tidal water level residuals did not improve the results at Truc Vert. However, this is
474 not a generic result as at Truc Vert, and along the entire Aquitaine coast studied here (Figure 1a), the
475 atmospheric surge is quite small (Le Cann, 1990) owing to the quite narrow continental shelf.
476 Atmospheric surge at Truc Vert at all the satellite flyover dates used here ranged from -0.27 m to
477 +0.29 m with a mean of -0.05 m (Figure 3e). This is small compared to the wave runup, ranging from
478 0.17 m to 1.89 m with a mean of 0.91 m (Figure 3f), and the meso-macrotidal tide range (Figure 3e).
479 However, including storm surge may be critical to improve shoreline estimation on coasts with small
480 tide range, but potentially large surge due to large and shallow continental shelf. For instance, sea
481 level can rise by metres due to atmospheric surge in the North Sea (Spencer et al., 2015), the Gulf of
482 Mexico (Sheng et al., 2004) or even c. 100 km north of the study area where the continental shelf
483 becomes much wider and shallower (Bertin et al., 2012). For energetic coasts with similar settings as
484 Truc Vert, overlooking atmospheric surge is acceptable, which is an advantage for practical
485 applications as accurate local surge hindcasts starting back in the 80s are scarce.

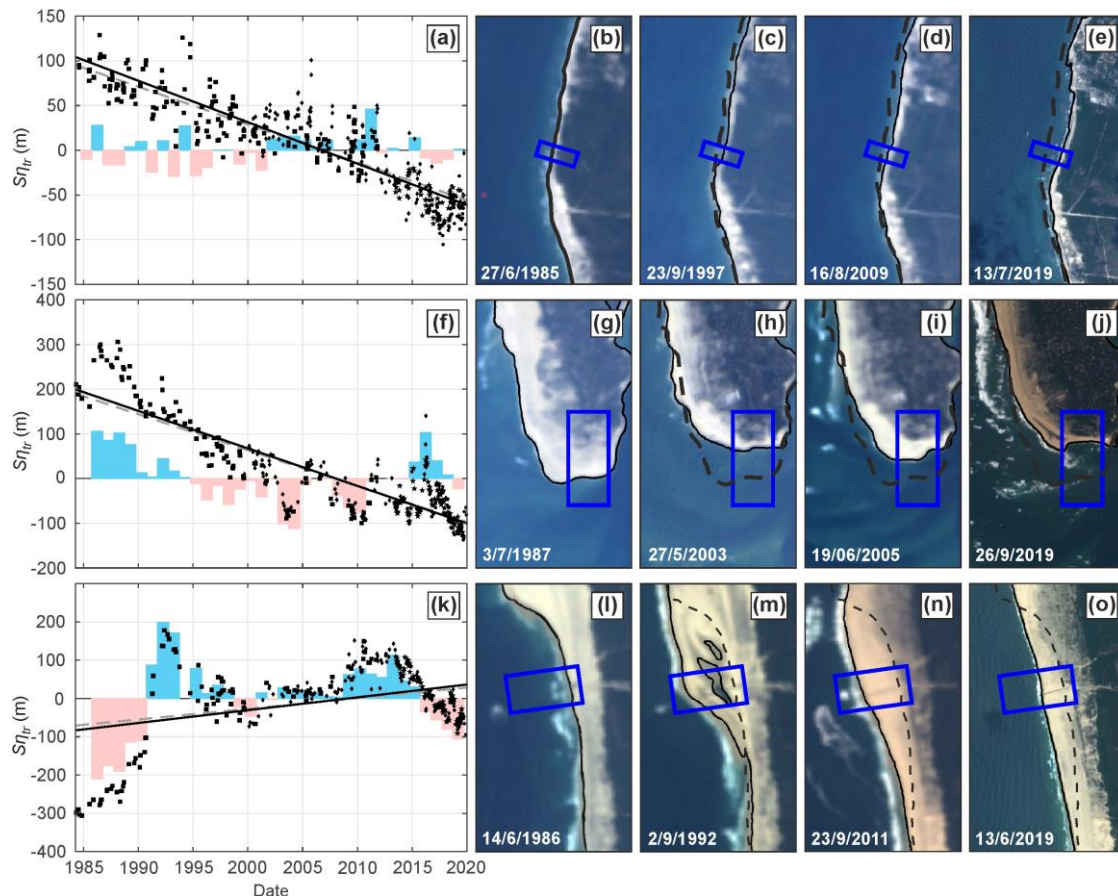
486 Another important parameter to quantify is the beach slope, which is used in traditional set-up and
487 runup formulas (Stockdon et al., 2006) and for tidal correction (Vos et al., 2019a). Nevertheless, using
488 a time- and space-varying slope does not improve shoreline reconstruction for Truc Vert, which is
489 another advantage for practical application as only an average beach slope value needs to be
490 provided. Recently, Vos et al. (2020) developed a simple and efficient approach to derive beach slope
491 from the same publicly available satellite images, making it possible to compute satellite shoreline
492 position without requiring local topographic data.

493 Our work has therefore identified key parameters contributing to shoreline error reduction through
494 the development of a robust methodology. These improvements need to be tested at other sites, in
495 particular on reflective gravel and mixed sand-gravel beaches, and ultra-dissipative sandy mega-tidal
496 beaches. Further possibility for uncertainty reduction concerns the georeferencing and the better
497 detection of the sand/water interface. The CoastSat waterline detection algorithm uses an image
498 classification based on a Neural Network trained at five beaches along the New South Wales coast
499 (Vos et al., 2019a). Training a new Neural Network for more representative sites may further improve
500 the sand/water interface detection. Overall, more work is required to identify and further address
501 other key sources of uncertainties, which is beyond the scope of the present paper.

502 The 35-year shoreline time series at Truc Vert (1984–2019) shows that more accurate assessment of
503 long-term shoreline trends and interannual variability can be computed than was achieved in
504 previous global studies (e.g., Luijendijk et al., 2018; Mentaschi et al., 2018). Similar trends are
505 obtained with $\tilde{S}\eta_{tr}$ (+0.50 m/yr) and $\tilde{S}\eta_0$ (+0.60 m/yr) (Figure 10b). However, shoreline trend

506 computation at other sites along the Aquitaine coast (e.g. Hourtin, Biscarrosse, Figure 1a) indicates
507 that much larger differences can be observed. $\tilde{S}\eta_0$, which does not account for water level
508 fluctuations, is close to the global approach in Luijendijk et al. (2018) who used yearly composite and
509 therefore averaged water level variations. A detailed inspection of the trends computed in Luijendijk
510 et al. (2018) at Truc Vert shows trends that are very different to those computed herein. The
511 dominant trend computed by Luijendijk et al. (2018) at Truc Vert indicates, strongly alongshore
512 variable, large, erosion at -1.13 m/yr averaged over the same 3500-m sector, peaking locally at 3.8
513 m/yr. A strong alongshore variability was also found in Mentaschi et al. (2018), although a direct
514 quantitative comparison could not be performed. This goes against decadal and multi-decadal
515 observations at this coast (e.g., Castelle et al., 2017a, 2018) and results presented herein, which all
516 concur to an alongshore-uniform c. +0.5 m/yr trend. It must be acknowledged that the comparison
517 above is performed between a site-specific analysis where the images were manually selected and a
518 runup correction was applied using a local wave and water level hindcast (our study), and a global
519 method that was applied over the whole world (Luijendijk et al., 2018; Mentaschi et al., 2018).

520 We therefore anticipate that the new approach proposed here can improve the accuracy of satellite
521 shoreline long-term trends and interannual variability along many coasts worldwide. However, at
522 rapidly evolving sections, improvements will be marginal. North of Truc Vert, at Cape Négade (Figure
523 1a), the long-term trend is reasonably steady at -4.63 m/yr for $\tilde{S}\eta_{tr}$ (Figure 11a-e), and is very similar
524 with all the other shoreline proxies (not shown). The same applies further south at the tip of the Cap
525 Ferret sand spit or at La Salie at each side of the Arcachon Lagoon tidal inlet, where large long-term
526 trends of +3.34 m/yr and -8.38 m/yr are computed, respectively. However, large cycles are observed
527 with some dramatic decadal trends. For instance, the shoreline at La Salie has been eroding by nearly
528 30 m/yr over the last seven years (Figure 11k), despite an overall positive shoreline trend since the
529 1980s. Therefore, except at Cape Négade, where chronic erosion is relatively steady, further
530 extrapolating these 35-year trends to estimate shoreline position by 2100 (Vousdoukas et al., 2020)
531 is questionable, because time scales of shoreline cycles are similar to the period of satellite data
532 availability.



533

534 Figure 11. Left-hand panels: time series of shoreline position at (a) Cape Négade, (f) Cap Ferret
 535 sandspit tip and (k) la Salie (see location map in Figure 1a) derived from satellite $\tilde{S}\eta_{tr}$. In the left-
 536 hand panels the linear shoreline trend for $\tilde{S}\eta_{tr}$ is indicated by the black dotted line. The coloured
 537 bars in (a,b) show the inter-annual variability (trend removed) in post-winter shoreline position.
 538 Right-hand panels: corresponding RGB images at different relevant stages of evolution, blue boxes
 539 indicate areas where shoreline positions were averaged alongshore to compute the time series
 540 shown in the left-hand panels.

541 We acknowledge that the concept of global application is very attractive and responds to strong
 542 demand. However, past shoreline trends estimations on beaches incurs large uncertainties, which
 543 become exacerbated if extrapolated in time to estimate future shoreline change. Vos et al. (2019a)
 544 recognised issues with dissipative and large tidal range sites. This work has identified key parameters
 545 contributing to large errors for this type of environment and developed a robust methodology for
 546 limiting uncertainty. Such approach requires accurate tide and inshore wave hindcasts, which can be
 547 challenging to obtain in complex coastal settings where, e.g., wave shadowing from offshore islands
 548 or offshore wave refraction can largely impact breaking wave conditions. These improvements need
 549 to be tested in other sites with similar tidal/wave forcing characteristics but different morphological
 550 and sediment characteristics. This will allow addressing the links between coastal response and large-

551 scale climate patterns of atmospheric variability in a wide range of environments. It will also provide
552 improved beach state classification and, where time scales of shoreline cycles are not similar to the
553 period of data availability (e.g. away from inlet and estuary mouths), less uncertain shoreline
554 projections by the end of the century in the context of climate change.

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