

Multi-decadal shoreline change in coastal Natural World Heritage Sites – a global assessment

Salma Sabour¹, Sally Brown², Robert J. Nicholls^{1,3}, Ivan D. Haigh⁴, Arjen P. Lujendijk^{5,6}

¹Faculty of Engineering and Physical Sciences, University of Southampton, Highfield, Southampton, SO17 1BJ, United Kingdom.

²Department of Life and Environmental Sciences, Bournemouth University, Fern Barrow, Bournemouth BH12 5BB, United Kingdom.

³Tyndall Centre for Climate Change Research, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, United Kingdom.

⁴School of Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, European Way, Southampton, SO14 3ZH, United Kingdom.

⁵Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

⁶Deltares, Delft, The Netherlands

May 2020

32 Abstract

33 Natural World Heritage Sites (NWHS), which are of Outstanding Universal Value, are increasingly
34 threatened by natural and anthropogenic pressures. This is especially true for coastal NWHS, which
35 are additionally subject to erosion and flooding. This paper assesses shoreline change from 1984 to
36 2016 within the boundaries of 67 designated sites, providing a first global consistent assessment of its
37 drivers. It develops a transferable methodology utilising new satellite-derived global shoreline
38 datasets, which are classified based on linearity of change against time and compared with global
39 datasets of geomorphology (topography, land cover, coastal type, and lithology), climate variability
40 and sea-level change. Significant shoreline change is observed on 14% of 52 coastal NWHS shorelines
41 that show the largest recessional and accretive trends (means of -3.4 m yr^{-1} and 3.5 m yr^{-1} ,
42 respectively). These rapid shoreline changes are found in low-lying shorelines ($< 1 \text{ m}$ elevation)
43 composed of unconsolidated sediments in vegetated tidal coastal systems (means of -7.7 m yr^{-1} and
44 12.5 m yr^{-1}), and vegetated tidal deltas at the mouth of large river systems (means of -6.9 and 11 m yr^{-1}).
45 Extreme shoreline changes occur as a result of redistribution of sediment driven by a combination
46 of geomorphological conditions with (1) specific natural coastal morphodynamics such as opening of
47 inlets (e.g. Río Plátano Biosphere Reserve) or gradients of alongshore sediment transport (e.g. *Namib*
48 *Sea*) and (2) direct or indirect human interferences with natural coastal processes such as sand
49 nourishment (e.g. *Wadden Sea*) and damming of river sediments upstream of a delta (e.g. *Danube*
50 *Delta*). The most stable soft coasts are associated with the protection of coral reef ecosystems (e.g.
51 *Great Barrier Reef*) which may be degraded/destroyed by climate change or human stress in the
52 future. A positive correlation between shoreline retreat and local relative sea-level change was
53 apparent in the *Wadden Sea*. However, globally, the effects of contemporary sea-level rise are not
54 apparent for coastal NWHS, but it is a major concern for the future reinforcing the shoreline dynamics
55 already being observed due to other drivers. Hence, future assessments of shoreline change need to
56 account of other drivers of coastal change in addition to sea-level rise projections. In conclusion,
57 extreme multi-decadal linear shoreline trends occur in coastal NWHS and are driven primarily by
58 sediment redistribution. Future exacerbation of these trends may affect heritage values and coastal
59 communities. Thus shoreline change should be considered in future management plans where
60 necessary. This approach provides a consistent method to assess NWHS which can be repeated and
61 help steer future management of these important sites.

62

63 **Keywords:** shoreline change, multi-decadal, local and global scales, UNESCO, conservation, World
64 Natural Heritage Sites, sea-level rise, coastal heritage, erosion, recession, accretion

65

66 1 Introduction

67 World Heritage Sites are locations of Outstanding Universal Values (OUV) selected by the United Nations
68 Educational, Scientific and Cultural Organization (UNESCO) as having cultural, historical, scientific, or other
69 forms of significance¹. Of the 1 092 World Heritage Sites, 209 are classified as Natural World Heritage Sites
70 (NWHS)¹. NWHS have a high irreplaceability (uniqueness or rarity) factor; they are prioritised and have
71 extraordinary biodiversity and geodiversity features compared to other protected areas^{2,3}. The UNESCO World
72 Heritage Centre established a list of 14 primary factors of deterioration of the OUV ranging from human
73 activities (development, pollution, social and cultural use), climate change and severe weather events, to
74 invasive species, management and institutional factors⁴. Climate change and severe weather events can affect
75 coastal areas through flooding, inundation and increased erosion⁵⁻⁷. 88 NWHS intersect the coast and include
76 sites most at risk from climate change⁸. Although they have pristine environments, their coastlines are
77 increasingly subject to anthropogenic pressures inside and outside their boundaries such as pollution,
78 population growth, and development including port facilities, dams and pumping stations. Following the
79 International Union for Conservation of Nature conservation Outlook assessment conducted in 2017⁹, only
80 20% of coastal NWHS have a good conservation outlook, and the conservation of 39% of the sites is under
81 significant to critical concerns. Moreover, the OUV of about two thirds of coastal NWHS are at high to very
82 high threat from deteriorating factors. Additionally, these sites are subject to physical processes such as sea-
83 level rise (SLR)¹⁰⁻¹⁵ and human modifications to sediment budgets¹⁶. However, shoreline change is not
84 systematically monitored or reported in many NWHS¹⁷⁻¹⁹, so it is unclear how NWHS shorelines have or could
85 change. As sites that have very limited internal anthropogenic disturbance, they present significant
86 opportunities to analyse how and why shorelines change due to natural drivers and/or external pressures.

87
88 Previous assessments of shoreline change in heritage studies include local²⁰⁻²³, regional²⁴ or global^{25,26} studies.
89 Local studies included the *Sundarbans* mangrove forests^{21,23}, the *Everglades National Park*²², and the *Wadden*
90 *Sea*²⁰. A regional evaluation of 49 coastal Cultural World Heritage Sites around the coast of the Mediterranean
91 found that 37 low-lying sites are at risk from a 100-year flood event today and that 42 sites are threatened by
92 coastal erosion²⁴. Two global studies have analysed the effects of future shoreline change due to SLR. The first
93 determined that 80% of the coastal wetlands of international importance could be affected by a 0-1 m rise in
94 sea level²⁷. The second study found that 40 to 136 cultural and mixed coastal World Heritage Sites may be
95 affected by flooding over 2 000 years if global temperatures and sea-levels continue to rise²⁵. To date, no study
96 has explored globally past multi-decadal shoreline change and its possible drivers in NWHS in term of their
97 geomorphology, elevation, land cover, lithology, climate variability and sea-level change.

98
99 The availability of satellite images from 1984 to present via the Google Earth Engine has allowed the creation
100 of a global consistent shoreline change dataset that can be used to monitor coastal NWHS²⁸⁻³⁰. In this paper,
101 global datasets of shorelines, geomorphological conditions, and relevant forcing drivers are used to evaluate
102 historic shoreline change from 1984 to 2016 across 67 coastal NWHS (out of 88 due to data availability
103 limitations and data cleaning). The objectives are:

- 104
105 (1) To assess and classify historic shoreline change behaviour within the 67 coastal NWHS;
106 (2) To evaluate the geomorphological conditions associated with different shoreline behaviours (based
107 on their linearity against time) and shoreline trends (recessional, depositional and stable); and
108 (3) To determine the impacts of historic sea-level change and climate variability on shoreline behaviour.

109
110 This paper is structured as follows. The data are introduced in Section 2. The methods and results are
111 presented in Section 3 and Section 4 respectively. The discussion is presented in Section 5 and the conclusion
112 in Section 6.

113
114
115

116 2 Data

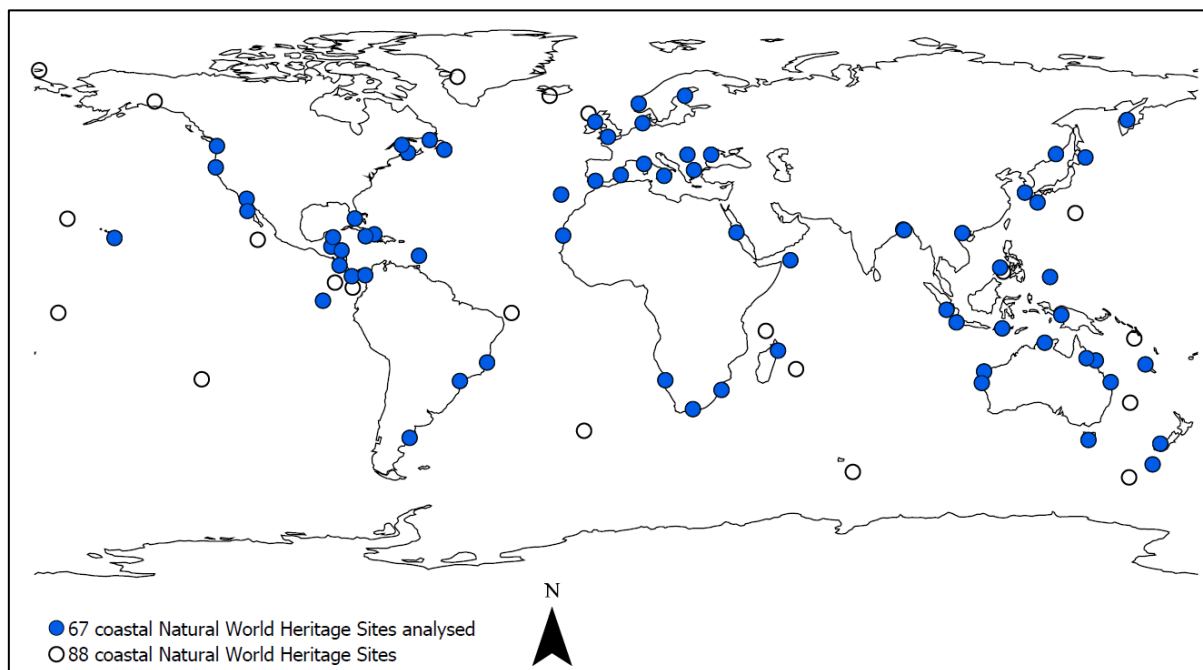
117 Three datasets were used: (1) coastal NWHs sites boundaries and shoreline change time series (Section 2.1);
118 (2) geomorphological datasets (Section 2.2); and (3) climate variability and sea-level change datasets (Section
119 2.3).

120

121 2.1 Study sites and shoreline change time series

122 Boundaries of coastal NWHs were retrieved from the World Database on Protected Areas³¹. 88 sites
123 intersected the Global, Self-consistent, Hierarchical, High-resolution Shoreline database³² (Figure 1).
124 Shorelines were obtained from a global assessment of derived Landsat images^{28–30}. This provided satellite-
125 derived shorelines (SDS) data points and their yearly positions based on transects spaced 500 m apart. SDS
126 data points were available for 71 out of 88 coastal NWHs due to limited coverage of historic satellite imagery
127 in offshore waters. The raw shoreline time-series data were cleaned from transects containing less than five
128 SDS data points and having a temporal coverage shorter than seven years²⁸. Approximately 1.5 million time-
129 series data points were selected. Further conditional and outlier data cleaning were undertaken
130 (Supplementary Section A.1.1). The conditional cleaning was performed for more consistency on the
131 assessment of shoreline trends: all transects that had at least 17 SDS data points were retained for the analysis
132 (Supplementary Section A.1.1). The outliers' cleaning was performed to delete extreme SDS data points values
133 (deviating by more than three times the standard deviation) within each transect (Supplementary Section
134 A.1.1). The cleaning process (see flowchart in Supplementary Figure SM1) removed 3.8% of the raw SDS data
135 points, and 67 sites remained in the analysis (Figure 1).

136



137

138 Figure 1 Geographical distribution of 88 coastal Natural World Heritage Sites around the world. 67 sites with available cleaned shoreline
139 time-series data are analysed (Sources: World Database on Protected Areas³¹, Global, Self-consistent, Hierarchical, High-resolution
140 Shoreline database³², and shoreline time-series data^{28–30}).

141

142 2.2 Geomorphological conditions

143 Information of topography, land cover, coastal type and lithology (Table 1) was obtained from global databases
144 to analyse how depositional and recessional shoreline change rates (SCR) varied (Supplementary Section
145 A.1.2). The resolution of the topography and land covers datasets (~500 m at the equator) is similar to the
146 shoreline data. The coastal type dataset resolution is 50 km and permits the classification of sites. The
147 resolution of lithological data varies, starting from 5 m² and is adequate for both transect- and site-based

148 analysis. These datasets are suitable due to their coverage of the study area allowing for a consistent analysis;
 149 moreover, their resolutions are suitable for a global and site-based assessment of shoreline trends.

150
 151 Table 1 Summary data types, sources, resolutions and transects categorisation in terms of topography, land cover, coastal typology,
 152 and lithology. Details of data selection and classification are available in the Supplementary Section A.1.2.

Dataset	Source and Resolution	Categories
Topography (classification based on the distribution of the elevation of strong linear transects)	Global Map DEM (2017) ³³ ~0.5km at the equator	<ol style="list-style-type: none"> 1. $0 \leq \text{elevation} \leq 1 \text{ m}$ (extremely low-lying) 2. $1 < \text{elevation} \leq 10 \text{ m}$ (low-lying) 3. $10 < \text{elevation} \leq 50 \text{ m}$ (middle) 4. $50 < \text{elevation} \leq 400 \text{ m}$ (high) 5. No data (transects without available elevation)
Land cover	Global Land Cover by National Mapping Organisations - GLCNMO (2013) ³⁴ ~0.5km at the equator	<ol style="list-style-type: none"> 1. Coral reefs 2. Mangroves 3. Marshes 4. Vegetated 5. Non-vegetated 6. Urban areas
Coastal type	Worldwide Typology of Nearshore Coastal Systems (2011) ³⁵ Minimum resolution 50km	<ol style="list-style-type: none"> 1. Small deltas 2. Tidal systems 3. Lagoons 4. Fjords and fjärds 5. Large rivers 6. Large rivers with tidal influence 7. Karst-dominated stretches of coasts 8. Arheic (dry areas) 9. Islands
Lithology	Global Lithological Map - GliM (2012) ³⁶ Average resolution of 1:3 750 000 – polygons areas varies starting from 5 m ²	<ol style="list-style-type: none"> 1. Evaporites 2. Polar ice and Glaciers 3. Acid Plutonic Rocks 4. Basic-Ultrabasic Plutonic Rocks 5. Intermediate Plutonic Rocks 6. Metamorphic Rocks 7. Carbonate Sedimentary Rocks 8. Mixed Sedimentary Rocks 9. Siliciclastic Sedimentary Rocks 10. Unconsolidated Sediments 11. Pyroclastic 12. Acid Volcanic Rocks 13. Basic Volcanic Rocks 14. Intermediate Volcanic Rocks

153
 154 2.3 Climate variability and sea-level change
 155 Between 1900 and 2016, global mean sea level has risen by 16-21 cm³⁷. However, the effect of local SLR on
 156 the shoreline variability is poorly understood as often exceeded by climate variability, local geomorphological
 157 conditions, and/or human interventions³⁸. Our study hypothesised that local trends of SLR³⁷ may have a
 158 potential observable contribution to strong linear shoreline trends within similar geomorphological categories
 159 in pristine NWHS sites, which should be negligibly affected by human interventions. To verify this hypothesis,
 160 local trends of sea-level change were assessed, and their effects on strong linear shoreline trends were
 161 determined within different geomorphological categories and sites. Linear available trends of local estimates
 162 of relative sea-level change³⁹ (measured by tide gauges) were used. These linear trends are appropriate as
 163 contemporary SLR acceleration rates are small (order of 0.1 mm² yr⁻¹) and are often not detectable at local
 164 tide gauge sites because of the large variability present in sea level⁴⁰. Other driving forces of regional climate
 165 variability⁴¹ (Table 2) were assessed as drivers of shoreline change. These yearly values of large-scale climate
 166 indices have been used in previous global assessments of surges and flooding^{42,43} and have been shown to
 167 influence year-to-year variability in sea level⁴⁴⁻⁴⁶. The shoreline change dataset is 33 years of length, which is

168 appropriate to capture the year-to-year variability that arises from climate forcing such as El Niño/Southern
 169 Oscillation (ENSO) or the other climate indices listed in Table 2.

170

171 Table 2 Regional climate variability indices description. The datasets are retrieved from <https://psl.noaa.gov/data/climateindices/list/>.

Index	Return periods	Description
El Niño/Southern Oscillation (ENSO) precipitation index	2 to 7 years ^{47,48}	Rainfall-based ENSO indices describing irregularly periodic variation in sea surface temperatures (SST) over the tropical eastern Pacific Ocean. The climate phenomenon periodically fluctuates between neutral, La Niña or El Niño ⁴⁹ .
Atlantic Multi-decadal Oscillation (AMO)	20 to 60 years ^{50,51}	SST anomalies occurring in the North Atlantic Ocean ⁵² .
Arctic Oscillation (AO)	No particular periodicity ⁵³	Non-seasonal sea-level pressure (SLP) anomalies at the Arctic and Antarctic poles ⁵⁴ .
North Atlantic Oscillation (NAO)	No particular periodicity ⁵⁵	Atmospheric SLP between the Icelandic Low and the Azores High, which affects the westerly winds and location of storm tracks ⁵⁶ .
Niño 3, Niño 4 and Niño 3.4	2 to 7 years ^{47,48}	Indices used to monitor the tropical Pacific, all of which are based on SST anomalies averaged across a given region ⁵⁷ .
North Pacific (NP)	2 to 6 years or 7 to 12 years ⁵⁸	Area-weighted SLP over the region 30°N-65°N, 160°E-140°W ⁵⁸ .
Pacific Decadal Oscillation (PDO)	20 to 30 years ⁵⁹	Leading principal component of North Pacific monthly SST variability ^{60,61} .
Southern Oscillation Index (SOI)	2 to 7 years ^{47,48}	Description of the development and intensity of El Niño or La Niña events in the Pacific Ocean (normalised index) ⁵⁷ .

172 3 Methods

173 Three stages of analysis were undertaken, corresponding to the three study objectives.

174

175 3.1 Shoreline change time-series: linear behaviour classifications and strong linear trends

176 Prior to fitting a linear regression, the potential linear behaviour of SDS data points, defined by their linearity
 177 against time, was assessed using Pearson's correlation coefficient (r) (R-3.5.1 package 'psych'⁶²), with the
 178 statistical significance measured using the p -value (the closer r is to +/- 1 the stronger the linear relationship).
 179 Based on past qualitative description of r^{63-65} , shoreline change transects were divided as:

180

- 181 1. Strong linear (less than -0.7 or greater than 0.7);
- 182 2. Weak linear (-0.7 to -0.3 or 0.3 to 0.7); and
- 183 3. Non-linear (-0.3 to 0.3).

184

185 To assess the contributions of the three linear categories in the long-term shoreline change, mean annual SCR
 186 for the three linear categories were assessed using an Ordinary Least Square linear regression applied to
 187 transects based SDS⁶⁶. The linear fit is a valid option to describe and forecast long-term predictive analysis and
 188 to minimise potential random error and short-time variability⁶⁶.

189

190 For the multi-decadal period considered in the analysis, linear regressions, which assume that the relationship
 191 between shoreline change and time is linear, are not relevant for shorelines changing with weak linear or non-
 192 linear behaviours. Thus, only SCR calculated for transects with strong linear shoreline behaviour are highly
 193 probable and significant on a multi-decadal scale and were selected to analyse depositional, recessional or
 194 stable SCR between 1984 and 2016. As the SDS accuracy is within a subpixel precision for the 33 years period
 195 analysed (15 m for Landsat), SCR between -0.5 and 0.5 m yr⁻¹ were considered stable²⁸. Depositional and
 196 recessional transects were defined by SCR >0.5 m yr⁻¹ and <-0.5 m yr⁻¹ respectively²⁸. The mean and standard
 197 deviation of SCR were calculated for each geomorphological category and sub-category. Geomorphological
 198 categories and sub-categories with less than five transects were considered non-representative of mean
 199 shoreline change per category. Shoreline change outliers for strong linear transects were removed (<-21.16 m
 200 yr⁻¹ for recessional transects and >23.05 m yr⁻¹ for depositional transects) (see Supplementary Figures SM10
 201 and SM11). 6 947 transects (98%) remained within 52 sites, after outliers were removed.

202

203 3.2 Geomorphological analysis

204 All transects were classified by their topography, land cover, coastal type and lithology (see Supplementary
205 Section A.1.2). A comparison of the different geomorphological conditions for the strong linear, weak linear
206 and non-linear shoreline behaviours has been conducted followed by an in-depth analysis of three transects'
207 types of strong linear behaviour: recessional, depositional and stable.
208

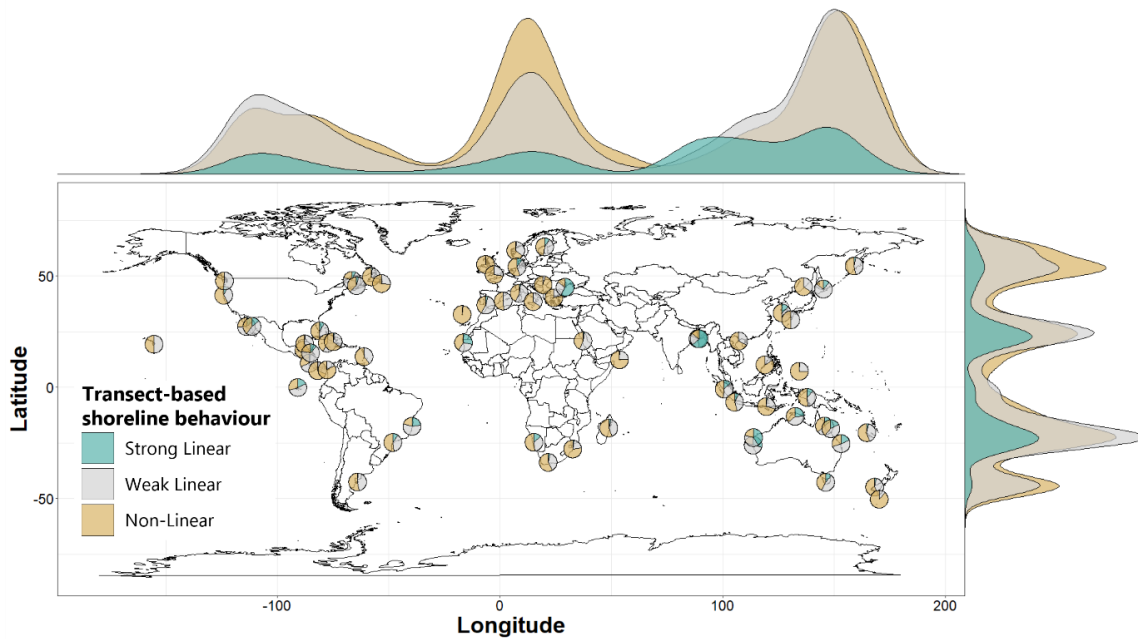
209 3.3 Climate variability and sea-level change analysis

210 Comparisons of SDS data points per transect against a time series of climate indexes were undertaken using
211 Kendall τ non-parametric rank correlation^{43,67}. The comparison investigated potential dependencies between
212 shoreline change and the ten climate indices defined in Section 2.3. The percentage of transects having a
213 moderate/strong positive ($\tau \geq 0.5$) or moderate/strong negative ($\tau \leq -0.5$) correlation with the time-series of
214 climate indices was assessed for each category of transects defined by the Pearson's r classification. The
215 contribution of sea-level change was assessed by fitting a linear regression between recessional and
216 depositional strong linear SCR and local relative sea-level change for different land cover and coastal type
217 categories. Additionally, a comparison between average shoreline evolution and relative sea-level change has
218 been conducted for each site. Only shores with a mean elevation lower than 10 m (definition of the Low
219 Elevation Coastal Zone⁶⁸) were assessed.

220 4 Results

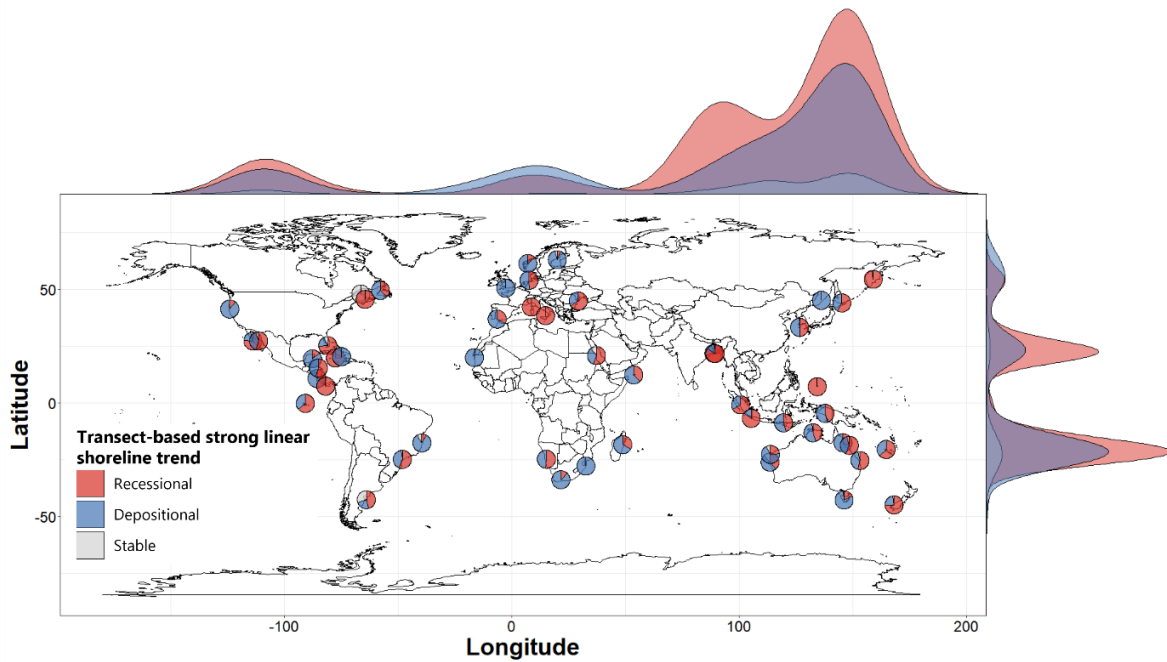
221 4.1 Classification of shoreline change time-series

222 The first objective was to assess and classify shoreline change linear behaviour in coastal NWHS between 1984
223 to 2016. All 67 sites had transects exhibiting at least two of the three linear shoreline behaviour categories
224 (defined in Section 3.1). 52 of the 67 sites contained transects with strong linear shoreline behaviour. Across
225 the 67 sites, data were available for 52 033 transects. 14% of these showed a significant strong linear
226 behaviour at the 99.85% confidence level (Supplementary Table SM4). The percentage of transects with linear
227 behaviour within each site varied from 0.2% (*Dorset and East Devon Coast*) to 63.5% (*The Sundarbans*) (Figure
228 2, Supplementary Table SM5). Under the hypothesis of long-term shoreline change, transects with strong
229 linear behaviour had the highest mean recessional (-3.4 m yr^{-1} , std 3.6 m yr^{-1}) and depositional trends (3.5 m
230 yr^{-1} , std 4.3 m yr^{-1}) in comparison to weak linear and non-linear shoreline categories (Supplementary Table
231 SM6). The differences between strong linear, weak linear and non-linear shoreline behaviours with both
232 depositional and recessional trends in relation to r are presented in Supplementary Table SM7 and Figures
233 SM4 to SM9.
234



235
 236 Figure 2 Globally distributed pie charts of strong linear, weak linear and non-linear transects (defined using Pearson's r coefficient)
 237 within the 67 coastal NWHS with available cleaned time-series shoreline data. The relative density plots show the relative distribution
 238 of each subset in relation to the complete dataset for the longitudes and the latitudes separately.
 239

240 For the 7 087 transects in the 52 coastal NWHS showing strong linear shoreline behaviour, 52.8% had a
 241 recessional trend, 43% were accreting and 4.2% were stable. Among the sites with more than five remaining
 242 linear transects, *The Sundarbans (Bangladesh)*, *Danube Delta (Romania)*, and *Sundarbans National Park (India)*
 243 had the highest percentage of transects with a strong linear behaviour. The *Volcanoes of Kamchatka (Russia)*,
 244 *The Sundarbans* and *Ujung Kulon National Park (Indonesia)* had the highest percentage of coasts with strong
 245 linear recessional shoreline change (97.6%, 84.9% and 84.6% were recessional of the total strong linear
 246 transects consecutively) (Figure 3). The *Banc d'Arguin National Park (Mauritania)*, *High Coast/Kvarken*
 247 *Archipelago (Sweden/Finland)*, and *Redwood National and State Parks (United States)* had the highest
 248 percentage with strong linear depositional shoreline change (98.3%, 91.1%, 90% are recessional of the total
 249 strong linear transects respectively) (Figure 3). Among all sites, *Río Plátano Biosphere Reserve (Honduras)* had
 250 the highest mean recessional SCR (-11.8 m yr^{-1} , std 7) and *The Wadden Sea (Netherland, Germany and*
 251 *Denmark)* had the highest mean depositional SCR (10.9 m yr^{-1} , std 5.7 m yr^{-1}) (Table 3).



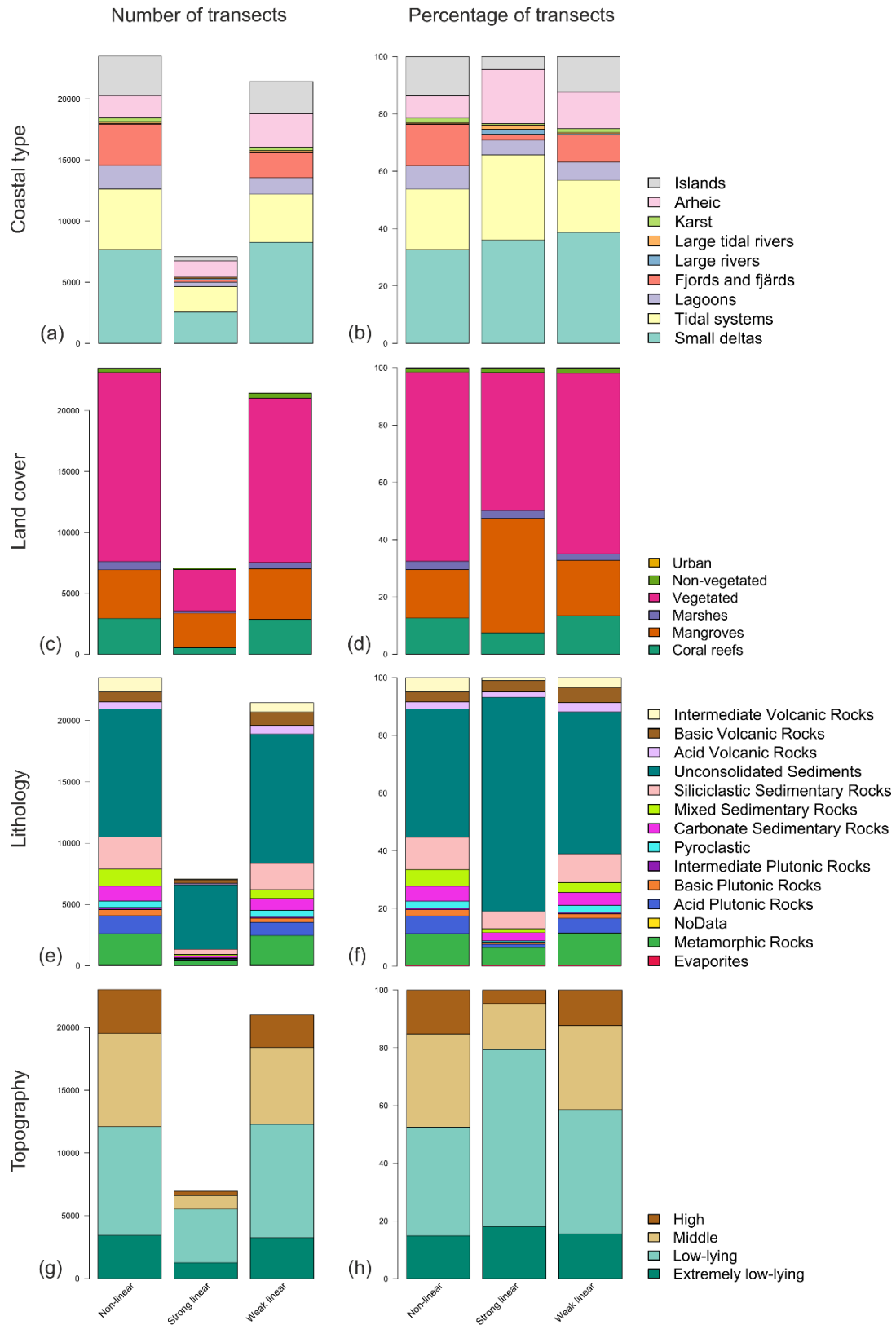
252
 253 Figure 3 Globally distributed pie charts of recessionary, depositional and stable shoreline trends within the 52 coastal NWHS with strong
 254 linear shoreline behaviour. The relative density plots show the relative distribution of each subset (recessionary, depositional and stable)
 255 in relation to the complete dataset for the longitudes and the latitudes separately. Detailed percentages for each site are available in
 256 the Supplementary Table SM8.

257
 258 Table 3 Number of transects, mean rates of change and standard deviations (std) for recessionary, depositional and stable shoreline
 259 trend categories within a subset of coastal NWHS with the highest values of mean strong linear recessionary and depositional trends.
 260 The sites, with more than five linear transects, are classified in descending order of the site-based mean rate of strong linear recessionary
 261 shoreline change rates. A comprehensive assessment for all sites is available in the Supplementary Table SM9.

Name	Coastline length (km)	Recessionary shoreline change			Depositional shoreline change			Stable shoreline change		
		Number of transects	Mean (m yr ⁻¹)	Std (m yr ⁻¹)	Number of transects	Mean (m yr ⁻¹)	Std (m yr ⁻¹)	Number of transects	Mean (m yr ⁻¹)	Std (m yr ⁻¹)
Río Plátano Biosphere Reserve	39	4	-11.8	7	4	2.7	2.8	0	0	0
Redwood National and State Parks	71	1	-9.3	0	9	3.7	2.1	0	0	0
Te Wahipounamu – South West New Zealand	1592.5	52	-8.6	6.7	21	1.8	0.7	2	-0.3	0.2
Socotra Archipelago	368	3	-7.8	0.9	5	5.4	1.5	0	0	0
The Wadden Sea	2 507.5	231	-7.5	4.6	240	10.9	5.7	0	0	0
Península Valdés	497	6	-7.2	5.4	3	0.7	0.2	4	0	0.4
Namib Sand Sea	359.5	46	-6.7	5	40	7.6	5.6	0	0	0
Atlantic Forest Southeast Reserves	382	41	-4.9	5.6	31	2.1	2.1	1	-0.4	0
The Sundarbans	503	528	-4.8	4	90	4.6	5.5	4	-0.4	0.1
Danube Delta	175.5	131	-4.6	2.9	66	4.6	4.9	0	0	0
Lorentz National Park	133.5	14	-4.3	4.7	16	6.6	4.8	0	0	0
Banc d'Arguin National Park	1 275	4	-1.8	1.3	227	6.1	3.9	0	0	0
iSimangaliso Wetland Park	66	0	0	0	10	4.9	1.2	0	0	0

262
 263 4.2 Geomorphological analysis
 264 The second objective was to evaluate the geomorphological conditions associated with different shoreline
 265 behaviours (based on their linearity against time) and shoreline trends (recessionary, depositional and stable).

266 First, a comparison of the geomorphological compositions of strong linear, weak linear and non-linear
267 shoreline behaviours was conducted (Figure 4). Transects with strong linear behaviour had a higher
268 percentage of tidal systems (30%) and arctic systems (19%) while transects with non-linear and weak linear
269 behaviours had a higher percentage of fjords/fjårds (14% and 9% consecutively) and islands (13% and 12%
270 consecutively). Strong linear transects had a higher percentage of mangroves (40%) in comparison to non-
271 linear and weak linear transects. Non-linear and weak linear transects had a higher percentage of different
272 rock types (such as metamorphic, acid plutonic, basic plutonic, intermediate plutonic rocks) while transects
273 with a strong linear behaviour had the highest percentage of unconsolidated sediments (74%). Transects with
274 strong linear behaviour had a higher percentage of extremely low-lying (18%) and low-lying areas (61%).



Classifications of shoreline behaviours

Figure 4 Number and percentage of transects for the three categories of shoreline behaviour: non-linear, weak linear and string linear classified by coastal type (a and b), land cover (c and d), lithology (e and f) and topography (g and h).

275
276
277
278
279
280

281 Second, the geomorphological conditions associated with strong linear recessional, depositional and stable
282 shoreline trends are evaluated. For 297 stable transects in 18 sites, 62% of the transects had their mean
283 elevation within [1-10 m] and 29% within [10-50 m]. Stable transects consisted of 42% small deltas, 31% arheic
284 systems and 13% tidal systems (Figure 5). Within these coastal types, vegetated areas and mangroves were
285 the prevailing land cover types (Figure 5). They represented respectively 53% and 34% of the totality of
286 recessional transects. 71% of recessional transects were unconsolidated sediments, 6% siliciclastic
287 sedimentary rock and 5% acid volcanic rocks. Further analysis were not conducted for stable strong linear
288 shoreline trend as they represent only 4% of the totality of strong linear transects in 35% of the sites displaying
289 a strong linear behaviour.

290
291 Within 3 664 recessional transects in 47 sites, 14% of the transects had their mean elevation within [0-1 m]
292 and 68% within [1-10 m]. Recessional transects consisted of 36% tidal systems, 36% small deltas and 15%
293 arheic systems (Figure 5). Within these coastal types, mangroves and vegetated areas were the prevailing land
294 cover type (Figure 5). They represented respectively 52% and 38% of the totality of recessional transects. 81%
295 of recessional transects were unconsolidated sediments, 6% siliciclastic sedimentary rock and 5% basic
296 volcanic rocks. Within 2 986 depositional transects in 45 sites, 23% of the transects had their mean elevation
297 within [0-1 m] and 51% within [1-10 m]. Depositional transects consisted of 36% small deltas, 23% tidal, and
298 23% arheic systems respectively (Figure 5). Within these coastal types, mangroves and vegetated areas were
299 dominant (Figure 5). Vegetated areas, mangroves and coral reefs represented respectively 60%, 25% and 11%
300 of the totality of accretive transects. 67% of accretive transects were unconsolidated sediments, 11%
301 metamorphic rocks and 7% siliciclastic sedimentary rocks. The depositional trend decreased exponentially
302 with increases in elevation (Supplementary Figure SM13). The highest depositional SCR were observed for
303 transects with a mean elevation lower than 1 m (Table 4).

304
305 Among all elevations categories, the comparison of land cover categories shows that transects within the
306 elevation category [0-1 m] with vegetated areas had the highest mean rate of shoreline recession (-5.9 m yr^{-1} ,
307 std 4.3 m yr^{-1}) (Table 4). Transects within a 1 km geodesic distance from coral reefs had the lowest recessional
308 trend (mean -1.7 m yr^{-1} , std 1.8 m yr^{-1}). For elevations $<1\text{m}$, among all geomorphological categories, the highest
309 mean rates of recession (-8.1 m yr^{-1} , std 5.2 m yr^{-1}) was observed in transects composed of unconsolidated
310 sediment within the category of vegetated tidal systems in the *Wadden Sea* (Supplementary Table SM10). For
311 low-lying areas, the highest mean recession of -8.9 m yr^{-1} (std 4.2 m yr^{-1}) was observed in transects composed
312 of siliciclastic sedimentary rocks within the category of vegetated tidal systems (Supplementary Table SM11).
313 For the middle-elevation category, the highest mean shoreline recessive trend was observed within
314 metamorphic rock transects situated in vegetated fjords (-7.5 m yr^{-1} , std 7.2 m yr^{-1}) in *Te Wahipounamu (New*
315 *Zealand)* (Supplementary Table SM12). For the high-elevation category, the greatest mean recession was in
316 metamorphic rock transects in vegetated fjords and fjårds situated in *Te Wahipounamu* and *West Norwegian*
317 *Fjords (Norway)* (-13.1 m yr^{-1} , std 6.2 m yr^{-1}) (Supplementary Table SM13).

318
319 For all topographic categories, extremely low-elevation transects within vegetated areas had the highest mean
320 accretive trend (7.0 m yr^{-1} , std 5.8 m yr^{-1}) (Table 4). Transects within a 1 km geodesic distance from coral reefs
321 had the lowest accretive trend (Table 4). Within extremely low-elevated transects, the highest mean accretive
322 trends were observed in transects composed of vegetated tidal systems (12.5 m yr^{-1} , std 5.4 m yr^{-1} , in the
323 *Wadden Sea*) and vegetated large rivers within a tidal delta (11.0 m yr^{-1} , std 5 m yr^{-1} , in the *Islands and*
324 *Protected Areas of the Gulf of California (Mexico)*) (Supplementary Table SM14). Within low-elevated
325 transects, the highest mean depositional trend of 13.6 m yr^{-1} (std. 5.3 m yr^{-1}) was observed in transects
326 composed of evaporites within the category of vegetated small deltas situated within the *Namib Sand Sea*
327 *(Namibia)* (Supplementary Table SM15). For the middle-elevation category, the highest accretive trend was
328 observed within transects situated in tidal coastal systems covered by mangroves (4.6 m yr^{-1} , std 5.4 m yr^{-1})
329 (Supplementary Table SM16). Coastal ecosystems with this shoreline trend were found in *Kakadu National*
330 *Park*, *Lorentz National Park* and *The Sundarbans*. For high elevation transects, the greatest mean accretive

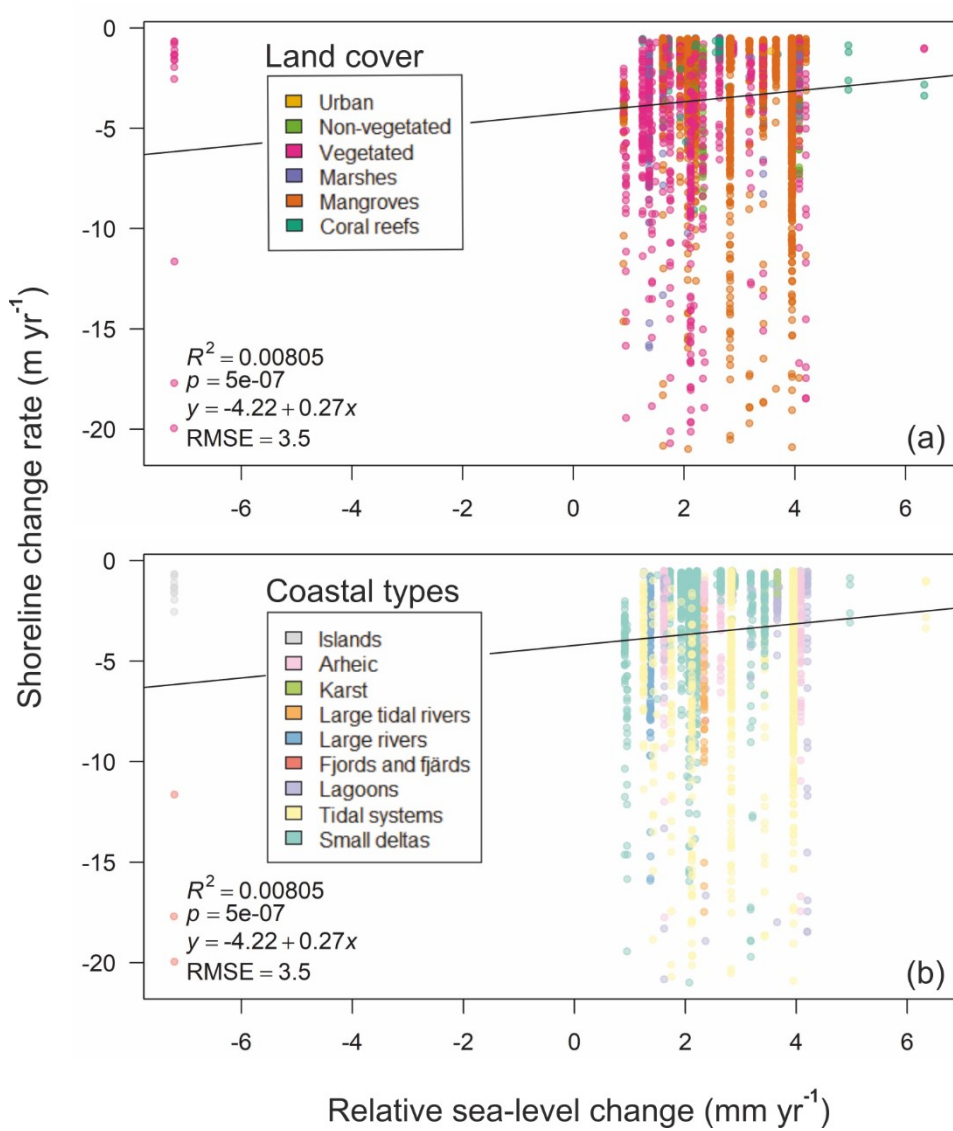
338 Table 4 Mean strong linear recessional and depositional shoreline change rates (m yr⁻¹) within the elevation categories and
 339 corresponding land cover sub-categories. Grey cells correspond to non-representative or non-existent categories. Categories with less
 340 than ≤ 5 transects are considered as non-representative of the shoreline change within each category. Detailed results for other
 341 geomorphological categories and subcategories are available in the Supplementary Sections A.2.3 and A.2.4.

Mean strong linear recessional and depositional shoreline trends for topographical and land cover categories (m yr ⁻¹)													
Topographical categories		Land cover categories											
		Coral reefs		Mangroves		Marshes		Vegetated		Non-vegetated		Urban	
0 ≤ elevation ≤ 1 m		-5.3	1	-3	3.7	-4.7	5.9	-5.9	7	-3.8	4.3		
-5.3 6.7													
1 < elevation ≤ 10 m		-3.1	1.6	-3.2	2.7	-3.1	2.9	-3.1	3.1	-3.3	2.4	-1.2	1.7
-3.1 2.7													
10 < elevation ≤ 50 m		-2.3	1.8	-2.4	2.5		1.7	-2.4	2	-1.7	1.2		
-2.3 2													
50 < elevation ≤ 400 m		-5.1	1					-5.5	1.5				
-5.1 1.4													

342

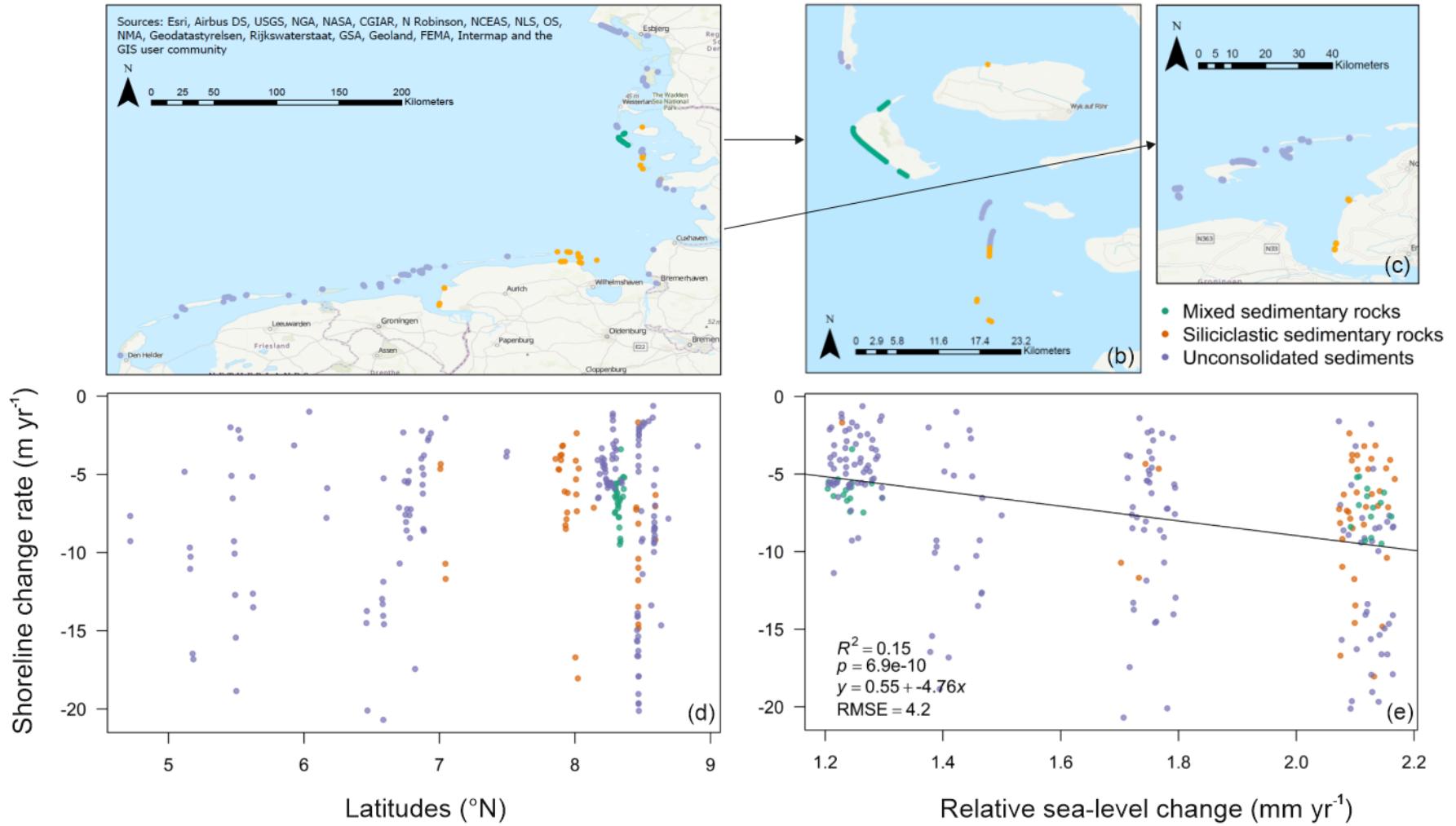
343 4.3 Climate variability and sea-level change analysis

344 The third objective was to determine the impacts of historic sea-level change and climate variability on
 345 shoreline behaviour in coastal NWHS. The comparison of yearly transect-based time series of shorelines
 346 (within the three categories of linear shoreline change behaviour) against ten climate indices indicated no
 347 significant statistical association at global scale (Supplementary Table SM18). Globally and for different
 348 geomorphological categories and sub-categories, there was no positive correlation between shoreline change
 349 and relative sea-level change for transects with strong linear recessional or depositional trend. Thus the
 350 absolute value of recessional SCR did not increase and the value of depositional SCR did not decrease with
 351 increasing relative sea-level change values for low lying transects (0 to 10 m) (Figure 6 and Supplementary
 352 Figure SM14). A weak positive relationship was observed between recessional strong linear shoreline trend
 353 and relative sea-level change in vegetated tidal systems below 1 m in the *Wadden Sea* (Figure 7). No
 354 correlation has been found between the average shoreline change rate and the average relative SLR for each
 355 site (Supplementary Figure SM15).



356
357
358
359

Figure 6 Correlation between recessional shoreline change rates and relative sea-level change for low lying transects (0 to 10 m) with a strong linear behaviour. The categorisation of transects is based on their land cover (a) and coastal type (b). The results for strong linear depositional shoreline trends are available in Supplementary Figure SM14.



361
362
363

Figure 7 (a), (b) and (c) Maps of strong linear recessional shoreline change positions for transects below 1 m in the *Wadden Sea* vegetated tidal systems. (d) Latitudinal distribution of shoreline change. (e) Correlation between strong linear recessional shoreline change rates and relative sea-level change. The categorisation of transects is based on their lithological categorisation.

364 5 Discussion

365 This paper has presented the first global assessment of trends and drivers of shoreline change in
366 coastal Natural World Heritage sites from 1984 to 2016. The data showed that both extreme erosional
367 and accretional tendencies were apparent and one tendency did not dominate in these sites. A
368 classification of linear behaviour with time indicated that strong linear shoreline trends have a
369 significant contribution to the recessional (-3.4 m yr^{-1} , std 3.6 m yr^{-1}) and depositional trends (3.5 m
370 yr^{-1} , std 4.3 m yr^{-1}). The prevalence of unconsolidated sediment in transects with strong linear
371 behaviour demonstrates the potential contribution of coastal sediment processes (affected by human
372 disturbances, waves, tides and tidal currents, wind, currents and sea-level change).

373
374 Drivers of strong linear recessional and depositional trends were assessed using geomorphological
375 categorisation of transects, including analysis of case studies (Supplementary A.3 Discussion). Low
376 lying transects had the highest mean depositional and recessional linear shoreline trends with (6.7 m
377 yr^{-1} and -5.3 m yr^{-1}) for transects in [0-1 m] and (2.7 m yr^{-1} and -3.1 m yr^{-1}) for transects in [1-10 m].
378 This is partly explained by the lithological compositions of these low-lying environments and the
379 presence of lagoons, sandy beaches, large rivers and large rivers under tidal influences. *Río Plátano*
380 *Biosphere Reserve* has the highest mean shoreline recession (-11.8 m yr^{-1} , std 7.01 m yr^{-1}) due to the
381 2002 opening of an inlet 12 km northwest of Iban lagoon inducing new accretive and erosive processes
382 within the site boundaries that are influenced by Paulaya river sediment discharge and the southeast-
383 northwest ocean current from Honduras to Yucatan⁶⁹. Sediment deposition, shaped by the Benguela
384 Upwelling system, southwest of the *Namib Sand Sea's* Conception Bay (evaporite basin) and Sandwich
385 harbour had induced the highest mean accretive shoreline of all coastal NWHS (13.6 m yr^{-1} , std 5.3 m
386 yr^{-1})⁷⁰. Transects with high mean rates of change (10.1 m yr^{-1} and -7 m yr^{-1}) were found in large rivers
387 within tidal delta situated in the vegetated shorelines of *Islands and Protected Areas of the Gulf of*
388 *California*. This extreme trend is linked to natural forcing (wave and tides) but also to the decadal
389 legacy of distant human alterations that interrupts completely constructive processes within the delta
390 and creates new hydrological circulations accompanied by “unnatural” erosive/accretive processes⁷¹⁻
391 ⁷³. High sedimentary movements, found in vegetated shores (6.9 m yr^{-1} and -5.1 m yr^{-1}) and marshes
392 (5.4 m yr^{-1} and -5.7 m yr^{-1}) in large river systems are due to the construction of engineered structures
393 along the rivers and on the coasts. These extreme rates are observed in the *Danube Delta* that
394 underwent a large decrease in its sediment discharge due to up-stream damming projects (1970 and
395 1983) in parallel to the undesirable effects of extreme downdrift erosion southward of Sulina Jetties
396 engineered in the second half of the 19th century⁷⁴⁻⁷⁷. Extreme rates of changes are also observed
397 within vegetated tidal systems (8.2 m yr^{-1} and -6.8 m yr^{-1}) and more specifically within barrier islands
398 in the *Wadden Sea*. The largest unbroken system of intertidal sand and mudflats in the world is a result
399 of dramatic morphodynamic adjustments due to land reclamation (at the boundaries of the NWHS)
400 within the climatic environment of the Frisian coast, which supported the reduction of inlet width (and
401 tidal prism) and thus the growth of the islands^{78,79}. The mainland and some islands of *the Wadden Sea*
402 are engineered (sand nourishment, breakwaters dykes, and dunes protection) and accretive transects
403 are prevalent (Supplementary Figure SM19)⁸⁰⁻⁸⁴. Thus, both depositional and recessional large
404 shoreline trends in coastal NWHS can be linked to coastlines that are highly altered by human
405 intervention external and internal to a site's boundaries.

406
407 Transects within small deltas and arheic systems inside 1 km geodesic buffer from coral reefs have the
408 lowest accretive and recessional shoreline trend (1.5 m yr^{-1} and -1.5 m yr^{-1}) and (1.7 m yr^{-1} and -0.9 m
409 yr^{-1}) respectively). This trend may be explained as coral reefs provide sediments and coastal protection
410 from waves, storms and floods and minimise the effects of coastal processes on the coastlines⁸⁵⁻⁸⁷.
411 Most of the sites with coral reefs (such as the *Great Barrier Reef (Australia)*, *Shark Bay (Australia)*, and
412 *Komodo National Park (Indonesia)*) are under frequent bleaching events in recent years (for instance
413 the third bleaching event 2014-2017 was among the worst ever observed)^{88,89}. Unconsolidated

414 sediments within tidal systems protected by coral reefs show less stability than non-tidal systems with
415 higher rates of erosion (-3.4 m/y; std 1 m/y) and accretion (2.1 m/y; std 1.5m/y) in the *Great Barrier*
416 *Reef and Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems*. The reef systems
417 within the latter coastal NWHs are among the most affected by present and projected future
418 bleaching events⁸⁸. Coral reefs also deteriorate through overfishing, sewage and agriculture pollution
419 and invasive species^{90,91}. Further deterioration of coral reefs would weaken their function to maintain
420 stable coastlines, especially beaches^{87,88}.

421
422 While the shoreline change dataset describes well the changes for continental unconsolidated
423 sediments or sedimentary rocks, it does not demonstrate well shoreline change for coastal transects
424 situated within complex narrow bodies of water as fjords (such as *Te Wahipounamu*, and the *West*
425 *Norwegian Fjords*) or remote rocky cliffs (such as the *Galapagos Islands*). A visual verification using
426 Google Time-lapse does not show the extreme linear shoreline trend captured by the SDS for these
427 natural systems and informs on the limitation of shoreline detection methodology using satellite
428 images. These errors may occur during (1) image detection: geometric distortion and radiometric
429 errors⁹² or (2) image processing: geo-rectification, ortho-rectification⁹³ and shoreline extraction.

430
431 Overall, there are no statistically significant correlations between transect-based shoreline change and
432 the climatic indices of sea surface temperature and pressure anomalies. This may be explained by the
433 limited spatial and temporal resolution of the climatic data and the underlying satellites images used
434 to assess shoreline trends. In Low Elevation Coastal Zones, the analysis of shoreline trends
435 demonstrate that no major historic role of relative sea-level change in accretional or recessional
436 shoreline trend can be identified. One issue is that SLR shows limited variability in time and space over
437 the study period. Further, the high variability at many sites emphasises that other processes, in
438 addition to SLR, are operating. This may be due to different responses of sites to sea-level change, the
439 lack of observations on coastal dynamics and their driving processes and that even in rapidly subsiding
440 coasts other processes (i.e. storms, wave action, human activities) may dominate the shoreline
441 trend^{38,94}. However, for transects below 1 m in the vegetated tidal sedimentary systems and marshes
442 of the *Wadden Sea*, a weak correlation between increasing relative sea-level and shoreline strong
443 linear retreat was detected. This may be explained by rising sea-levels resulting in more inundation
444 but also coastal erosion in low-lying areas^{95,96}. The detection of this weak correlation may be related
445 to the better quality of tide gauge data available in the *Wadden Sea* and to the site's highly dynamic
446 tidally influenced inlets that experience one of the highest mean recession (-8.1 m yr⁻¹, std 5.2 m yr⁻¹)
447 in NWHs worldwide^{78,97}. This finding is supported due to the accuracy of shoreline detection methods
448 (0.5 m yr⁻¹) allowing observation of increased shoreline change as a result of SLR. For instance,
449 following the Bruun rule⁹⁸, 1 mm yr⁻¹ of SLR could induce at least an incremental horizontal change of
450 1.65 m in a beach slope of 1:50 over 33 years. Detection of climate variability and sea-level change
451 effects on shoreline behaviour could be improved by using higher satellites image resolution (e.g. 1m),
452 developing monthly time-series of shoreline change (instead of annual time-series) and improving the
453 spatial and temporal resolution of sea level and climatic data especially in remote areas.

454
455 The intensification of human interferences, climate change, SLR and wave climate change will affect
456 coastal processes inducing variations in sediment-budgets⁹⁹. Future SLR may become the main driver
457 of recession⁹⁹ effecting geomorphological responses. Eroding low-lying shorelines within tidal
458 systems, large rivers and large rivers under tidal influences, altered by human interferences to coastal
459 processes, may become the most affected coastal NWHs by future SLR and its related changes in
460 sediment dynamics. In the *Wadden Sea* while contemporary slow sea-level change has expressed itself
461 in losses of beaches or island displacements¹⁰⁰⁻¹⁰², future acceleration of SLR may induce back-barrier
462 erosion and sediment deficit in the tidal basin and result in the transformation of the inter-tidal system
463 to a lagoon system^{20,103}. The mapping of shoreline linear behaviour and depositional/recessional
464 trends distinguishing abrupt and gradual changes at the transect level, coupled with socio-economic

465 and ecologic indicators, can be used by coastal managers as a preliminary classification of shorelines
466 in term of the importance and urgency of their management, supporting NWS conservation triage
467 (process of prioritising actions)^{104,105}. The enhanced predictive capacity of strong linear shoreline
468 behaviour and the improved understanding of the factors causing this strong linear changes need to
469 be followed by more appropriate management actions, monitoring and planning of coastal NWS
470 sites' evolving shorelines (when required and to the extent possible). Unconsolidated sediment
471 shorelines in coastal NWS, not affected by external human interferences, which exhibit a strong
472 linear behaviour of shoreline change, may become primary observatories to assess SLR impacts on
473 natural coastal processes such as in *Río Plátano Biosphere Reserve* and the *Namib Sea*. Thus, this study
474 contributes to informing coastal management plans and decisions of coastal and marine protected
475 areas by providing a quantitative evaluation of shoreline behaviour that could improve the guide for
476 Planners and Managers for Marine and Coastal Protected Areas (developed by Salm & Clark¹⁰⁶).

477 6 Conclusions

478 Despite the high local and international values of coastal NWS, shoreline change has not been
479 systematically monitored or reported to date. Therefore, it was unclear how NWS coasts have been
480 changing across the world. This study comprises the first global assessment of multi-decadal shoreline
481 change from 1984 to 2016 within coastal NWS asking: "how are coastal NWS shorelines changing
482 around the world and why?".

483
484 Based on newly available open-access datasets, shoreline change was analysed for 67 NWS
485 worldwide, in terms of linear behaviour, recessional or accretive trends, and potential drivers of
486 change. Shorelines with strong linear erosional or accretive trends comprise 14% of total coastal
487 NWS shorelines. They occur within 52 coastal NWS and demonstrate the largest shoreline erosive
488 and accretive trends (mean of -3.4 m yr^{-1} and 3.5 m yr^{-1} , respectively). Among the transects with strong
489 linear behaviour, the highest recessional and accretive trends are found within low-lying
490 unconsolidated sediments shorelines ($< 1\text{m}$) in vegetated tidal coastal systems, and vegetated tidal
491 deltas at the mouth of large river systems. These extreme shoreline trends can be linked to natural
492 coastal morphodynamics such as the opening of inlets or gradient of alongshore sediment transport.
493 In other cases, they can be associated with direct or indirect human interferences such as land
494 reclamation and damming of rivers upstream of a delta. Conversely, the most stable soft coasts are
495 associated with shorelines protected by coral reefs ecosystems. In the future, these shorelines may
496 be subject to increased instability due to the intensification of climate change and human
497 deterioration degrading the natural protective capacity of coral reefs. A positive correlation between
498 recessional (strong linear) shoreline change and relative sea-level change was found in the *Wadden*
499 *Sea*, but globally, the effects of SLR on shoreline change are not apparent.

500
501 In most cases, shoreline monitoring had not been the main priority in the management of coastal
502 NWS. The availability of open-access datasets creates opportunities to better understand shoreline
503 change so to inform management actions where necessary. These analyses can be repeated and
504 refined providing new insights, as data extend in time and improve in resolution. Continued systematic
505 monitoring is advised, especially for sites undergoing direct or indirect human interference.

506
507
508
509

510 7 Acknowledgements

511 We acknowledge the researchers at Deltares for their support throughout this project. We thank all
512 the researchers who have made their global datasets available. Salma Sabour received funding via the
513 Leverhulme Trust Doctoral Training Scheme, hosted by Southampton Marine and Maritime Institute
514 at the University of Southampton.

515

516

517 8 Data availability statement

518

519 The data that support the findings of this study are openly available at
520 <http://doi.org/10.5281/zenodo.3751980>.

521 Interactive maps based on the linear classification and on the strong linear trends of coastal NWHS
522 transects are available at <https://salmasabour.github.io/shoreline-change-coastal-natural-heritage-UNESCO/shoreline-linear-behaviours/> and <https://salmasabour.github.io/shoreline-change-coastal-natural-heritage-UNESCO/shoreline-strong-linear-trends/> respectively.

524

525 9 Bibliography

- 526 1. UNESCO. *Operational Guidelines for the Implementation of the World Heritage Convention*.
527 <https://whc.unesco.org/en/guidelines/> (2017).
- 528 2. Le Saout, S. *et al.* Protected areas and effective biodiversity conservation. Supplementary
529 Material. *Science (80-.)*. **342**, 803–5 (2013).
- 530 3. Bertzky, B. *et al.* *Terrestrial Biodiversity and the World Heritage List*.
531 <https://portals.iucn.org/library/sites/library/files/documents/2013-016.pdf> (2014).
- 532 4. UNESCO WHC. UNESCO World Heritage Centre - List of factors affecting the properties.
533 <http://whc.unesco.org/en/factors/> (2008).
- 534 5. Dawson, R. J. *et al.* Integrated analysis of risks of coastal flooding and cliff erosion under
535 scenarios of long term change. *Clim. Change* **95**, 249–288 (2009).
- 536 6. Sweet, W. V *et al.* Global and Regional Sea Level Rise Scenarios for the United States. 1–75
537 (2017).
- 538 7. Rasmussen, D. J. *et al.* Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature
539 stabilization targets in the 21st and 22nd centuries. *Environ. Res. Lett.* **13**, 034040 (2018).
- 540 8. Perry, J. World Heritage hot spots: A global model identifies the 16 natural heritage properties
541 on the World Heritage List most at risk from climate change. *Int. J. Herit. Stud.* **17**, 426–441
542 (2011).
- 543 9. IUCN. *A conservation assessment of all natural World Heritage sites*. (2017).
544 doi:10.2305/IUCN.CH.2017.17.en.
- 545 10. Nicholls, R. J. Impacts of and Responses to Sea-Level Rise. in *Understanding Sea-Level Rise and*
546 *Variability* 17–51 (2010). doi:10.1002/9781444323276.ch2.
- 547 11. Vitousek, S. *et al.* Doubling of coastal flooding frequency within decades due to sea-level rise.
548 *Sci. Rep.* **7**, 1399 (2017).
- 549 12. Church *et al.* Sea-Level Rise by 2100. *Science (80-.)*. **342**, 1445–1445 (2013).
- 550 13. Gregory, J. Projections of Sea Level Rise. *IPCC Fifth Assess. Rep.* 16 (2013).
- 551 14. Goodwin, P., Haigh, I. D., Rohling, E. J. & Slangen, A. A new approach to projecting 21st century
552 sea-level changes and extremes. *Earth's Futur.* (2017) doi:10.1002/2016EF000508.
- 553 15. Brown, S. *et al.* Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and
554 1.5 and 2.0 °C Rise in Global Temperatures to Year 2300. *Earth's Futur.* (2018)
555 doi:10.1002/2017EF000738.
- 556 16. Dunn, F. E. *et al.* Projections of declining fluvial sediment delivery to major deltas worldwide in
557 response to climate change and anthropogenic stress. *Environ. Res. Lett.* **14**, (2019).
- 558 17. IUCN. *IUCN World Heritage Outlook*. (2017).
- 559 18. IUCN. IUCN Conservation Outlook Assessments - Guidelines for their application to natural
560 World Heritage Sites. **2**, 1–35 (2012).
- 561 19. UNESCO. Climate Change and World Heritage: Report on predicting and managing the impacts
562 of climate change on World Heritage and strategy to assist State Parties to implement
563 appropriate management responses. *World Herit. Reports* **22**, 1–55 (2007).
- 564 20. Trilateral Working Group on Coastal Protection and Sea Level Rise. Final Report of the Trilateral
565 Working Group on Coastal Protection and Sea Level Rise. *Wadden Sea Ecosyst.* **13**, 64 (2001).
- 566 21. Pahlwan, E. U. & Hossain, A. T. M. S. A disparity between erosional hazard and accretion of
567 the sundarbans with its adjacent east coast, Bangladesh: a remote sensing and GIS approach.
568 in *Volume 9644 SPIE Remote Sensing 96441G* (2015). doi:10.1117/12.2196386.
- 569 22. Park, J., Stabenau, E., Redwine, J. & Kotun, K. South Florida's Encroachment of the Sea and
570 Environmental Transformation over the 21st Century. *J. Mar. Sci. Eng.* **5**, 31 (2017).
- 571 23. Loucks, C., Barber-Meyer, S., Hossain, A. A., Barlow, A. & Chowdhury, R. M. Sea level rise and
572 tigers: Predicted impacts to Bangladesh's Sundarbans mangroves. *Clim. Change* **98**, 291–298
573 (2009).
- 574 24. Reimann, L., Vafeidis, A. T., Brown, S., Hinkel, J. & Tol, R. S. J. Mediterranean UNESCO World

- 575 Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nat. Commun.* **9**, (2018).
- 576 25. Marzeion, B. & Levermann, A. Loss of cultural world heritage and currently inhabited places to
577 sea-level rise. *Environ. Res. Lett.* **9**, 034001 (2014).
- 578 26. Sherbinin, A. de & Lacko, A. Evaluating the risk to Ramsar Sites from climate change induced
579 sea level rise. *Ramsar Sci. Tech. Brief. Note* **5**, (2012).
- 580 27. Sherbinin, A. de, Lacko, A., Alexander, S. & Rep-, S. Evaluating the risk to Ramsar Sites from
581 climate change induced sea level rise. *Ramsar Sci. Tech. Brief. Note* **5**, (2012).
- 582 28. Luijendijk, A. *et al.* The State of the World's Beaches. *Sci. Rep.* **8**, 1–11 (2018).
- 583 29. Hagenars, G., de Vries, S., Luijendijk, A. P., de Boer, W. P. & Reniers, A. J. H. M. On the accuracy
584 of automated shoreline detection derived from satellite imagery: A case study of the sand
585 motor mega-scale nourishment. *Coast. Eng.* **133**, 113–125 (2018).
- 586 30. Hagenars, G., Luijendijk, A., De Vries, S. & De Boer, W. Long term coastline monitoring derived
587 from satellite imagery. in *Coastal Dynamics* 1551–1562 (2017).
- 588 31. IUCN. Protected Planet. *Database* 1–9 <https://www.protectedplanet.net/> (2010).
- 589 32. Wessel, P. & Smith, W. H. F. A global, self-consistent, hierarchical, high-resolution shoreline
590 database. *J. Geophys. Res. Solid Earth* **101**, 8741–8743 (1996).
- 591 33. International Steering Committee for Global Mapping. Global Map data archives.
592 <https://globalmaps.github.io/>.
- 593 34. Kobayashi, T. *et al.* Production of Global Land Cover Data – GLCNMO2013. *J. Geogr. Geol.* **9**, 1
594 (2017).
- 595 35. Dürr, H. H. *et al.* Worldwide Typology of Nearshore Coastal Systems: Defining the Estuarine
596 Filter of River Inputs to the Oceans. *Estuaries and Coasts* **34**, 441–458 (2011).
- 597 36. Hartmann, J. & Moosdorf, N. The new global lithological map database GLiM: A representation
598 of rock properties at the Earth surface. *Geochemistry, Geophys. Geosystems* **13**, 1–37 (2012).
- 599 37. Church, J. a. *et al.* Sea level change. *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to*
600 *Fifth Assess. Rep. Intergov. Panel Clim. Chang.* 1137–1216 (2013)
601 doi:10.1017/CB09781107415315.026.
- 602 38. Le Cozannet, G., Garcin, M., Yates, M., Idier, D. & Meyssignac, B. Approaches to evaluate the
603 recent impacts of sea-level rise on shoreline changes. *Earth-Science Reviews* vol. 138 47–60
604 (2014).
- 605 39. NOAA. Sea Level Trends. *Tides Curr.* 2012 (2012).
- 606 40. Haigh, I. D. *et al.* Timescales for detecting a significant acceleration in sea level rise. *Nat.*
607 *Commun.* **5**, 1–11 (2014).
- 608 41. NOAA. ESRL : PSD : Climate Indices: Monthly Atmospheric and Ocean Time Series.
609 <https://www.esrl.noaa.gov/psd/data/climateindices/list/>.
- 610 42. Mawdsley, R. J. & Haigh, I. D. Spatial and Temporal Variability and Long-Term Trends in Skew
611 Surges Globally. *Front. Mar. Sci.* **3**, 1–17 (2016).
- 612 43. Muis, S., Haigh, I. D., Guimarães Nobre, G., Aerts, J. C. J. H. & Ward, P. J. Influence of El Niño-
613 Southern Oscillation on Global Coastal Flooding. *Earth's Futur.* **6**, 1311–1322 (2018).
- 614 44. White, N. J. *et al.* Australian sea levels-Trends, regional variability and influencing factors.
615 *Earth-Science Rev.* **136**, 155–174 (2014).
- 616 45. McCarthy, G. D., Haigh, I. D., Hirschi, J. J. M., Grist, J. P. & Smeed, D. A. Ocean impact on decadal
617 Atlantic climate variability revealed by sea-level observations. *Nature* **521**, 508–510 (2015).
- 618 46. Amiruddin, A. M., Haigh, I. D., Tsimplis, M. N., Calafat, F. M. & Dangendorf, S. The seasonal
619 cycle and variability of sea level in the South China Sea. *J. Geophys. Res. Ocean.* **120**, 5490–
620 5513 (2015).
- 621 47. NOAA. Climate Prediction Center - ENSO Cycle.
622 https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/ensocycle.shtml.
- 623 48. NOAA. El Nino/Southern Oscillation (ENSO) | Teleconnections | National Centers for
624 Environmental Information (NCEI). <https://www.ncdc.noaa.gov/teleconnections/enso/>.
- 625 49. Curtis, S., Adler, R., Curtis, S. & Adler, R. ENSO Indices Based on Patterns of Satellite-Derived

- 626 Precipitation. [http://dx.doi.org/10.1175/1520-0442\(2000\)013<2786:EIBOPO>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2000)013<2786:EIBOPO>2.0.CO;2) (2000)
627 doi:10.1175/1520-0442(2000)013<2786:EIBOPO>2.0.CO;2.
- 628 50. Christensen, J. H. *et al.* Climate phenomena and their relevance for future regional climate
629 change. *Clim. Chang. 2013 Phys. Sci. Basis Work. Gr. I Contrib. to Fifth Assess. Rep. Intergov.*
630 *Panel Clim. Chang.* **9781107057**, 1217–1308 (2013).
- 631 51. Gutiérrez, O. *et al.* Climate teleconnections and indicators of coastal systems response. *Ocean*
632 *Coast. Manag.* **122**, 64–76 (2016).
- 633 52. Enfield, D. B., Mestas-Nuñez, A. M. & Trimble, P. J. The Atlantic Multidecadal Oscillation and its
634 relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.* **28**, 2077–2080
635 (2001).
- 636 53. JISAO. Arctic Oscillation (AO). <http://research.jisao.washington.edu/data/aots/>.
- 637 54. NOAA. Climate Prediction Center - Arctic Oscillation.
638 https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml.
- 639 55. NOAA. North Atlantic Oscillation (NAO). 1–2 (2015).
- 640 56. NOAA. Climate Prediction Center - Northern Hemisphere Teleconnection Patterns.
641 <https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>.
- 642 57. NOAA. Climate Prediction Center - Monitoring & Data: Current Monthly Atmospheric and Sea
643 Surface Temperatures Index Values. <https://www.cpc.ncep.noaa.gov/data/indices/>.
- 644 58. Trenberth, K. E. & Hurrell, J. W. Decadal atmosphere-ocean variations in the Pacific. *Clim. Dyn.*
645 **9**, 303–319 (1994).
- 646 59. JISAO. Pacific Decadal Oscillation (PDO). in doi:10.4135/9781446247501.n2786.
- 647 60. Mantua, N. J. *et al.* A Pacific Interdecadal Climate Oscillation with Impacts on Salmon
648 Production**. [https://doi.org/10.1175/1520-0477\(1997\)078<1069:APICOW>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2) (1997)
649 doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.
- 650 61. Zhang, Y. *et al.* ENSO-like Interdecadal Variability: 1900–93. [http://dx.doi.org/10.1175/1520-0442\(1997\)010<1004:ELIV>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(1997)010<1004:ELIV>2.0.CO;2)
651 (1997) doi:10.1175/1520-0442(1997)010<1004:ELIV>2.0.CO;2.
- 652 62. Revelle, W. *Package 'psych'*. <https://personality-project.org/r/psych> (2019).
- 653 63. MM, M. Statistics Corner: A guide to appropriate use of Correlation coefficient in medical
654 research. *Malawi Med. J.* **24**, 69–71 (2012).
- 655 64. Asuero, A. G., Sayago, A. & González, A. G. The correlation coefficient: An overview. *Crit. Rev.*
656 *Anal. Chem.* **36**, 41–59 (2006).
- 657 65. Taylor, R. Interpretation of the Correlation Coefficient: A Basic Review. *J. Diagnostic Med.*
658 *Sonogr.* **6**, 35–39 (1990).
- 659 66. Dolan, R., Fenster, M. S. & Holme, S. J. Temporal Analysis of Shoreline Recession and Accretion.
660 *Source J. Coast. Res.* **721528**, 723–744 (1991).
- 661 67. Corbella, S. & Stretch, D. D. D. Decadal trends in beach morphology on the east coast of South
662 Africa and likely causative factors. *Nat. Hazards Earth Syst. Sci.* **12**, 2515–2527 (2012).
- 663 68. Socioeconomic Data and Applications Center (SEDAC)CIESIN, Earth Institute at Columbia
664 University Palisades, N. Y. [ciesin.columbia.eduNational. A. and S. A. Low-Elevation Coastal
665 Zone \(LECZ \). 2016](http://ciesin.columbia.edu/National_A_and_S_A_Low-Elevation_Coastal_Zone_(LECZ).2016) (2016).
- 666 69. Burke, L. & Sugg, Z. Hydrologic Modeling of Watersheds Discharging Adjacent to the
667 Mesoamerican Reef. *World Resour. Inst.* **35** (2006).
- 668 70. Berger, W. H., Lange, C. B. & Wefer, G. Upwelling history of the Benguela-Namibia system: A
669 synthesis of Leg 175 results. *Proc. Ocean Drill. Progr. Sci. Results* **175**, 1–53 (2002).
- 670 71. Andel, V. & G, T. S. Marine Geology of the Gulf of California. *Limnol. Oceanogr.* **10**, 303–304
671 (1965).
- 672 72. Glenn, E. P., Flessa, K. W. & Pitt, J. Restoration potential of the aquatic ecosystems of the
673 Colorado River Delta, Mexico: Introduction to special issue on 'Wetlands of the Colorado River
674 Delta'. *Ecol. Eng.* **59**, 1–6 (2013).
- 675 73. Pitt, J. Shaping the 2014 Colorado River Delta pulse flow: Rapid environmental flow design for
676

- 677 ecological outcomes and scientific learning. *Ecol. Eng.* **106**, 704–714 (2017).
- 678 74. Stănică, A., Panin, N., Staˇnicaˇ, A. & Panin, N. Present evolution and future
679 predictions for the deltaic coastal zone between the Sulina and Sf. Gheorghe Danube river
680 mouths (Romania). *Geomorphology* **107**, 41–46 (2009).
- 681 75. Claudino-Sales, V. Danube Delta, Romania. in *Coastal Research Library* vol. 28 93–97 (2019).
- 682 76. Ionescu, I. & Noaje, I. Natural environment change detection in Danube Delta, based on HRV -
683 SPOT images. *Int. J.* (1993).
- 684 77. Dan, S. *Coastal Dynamics of the Danube Delta*. (2013). doi:10.4233/uuid:9c19651e-e744-43c3-
685 aa85-7ea7abd14a2.
- 686 78. Kunz, H. Groynes on the East Frisian Islands: History and Experiences. in *Coastal Engineering*
687 *1996* 2128–2141 (American Society of Civil Engineers, 1997).
688 doi:10.1061/9780784402429.165.
- 689 79. Winter, C. Macro scale morphodynamics of the German North Sea coast. *J. Coast. Res. n SPEC.*
690 **IS**, 706–710 (2011).
- 691 80. Trilateral Working Group on Coastal Protection and Sea Level Rise. *CPSL Third Report. Wadden*
692 *Sea Ecosystem* vol. 28 (2010).
- 693 81. Trilateral Working Group on Coastal Protection and Sea Level Rise. *Coastal Protection and Sea*
694 *Level Rise: solutions for sustainable coastal protection in the Wadden Sea Region. Zhurnal*
695 *Eksperimental'noi i Teoreticheskoi Fiziki*
696 <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:No+Title#0> (2005).
- 697 82. Moser, M. & Brown, A. Trilateral Wadden Sea Cooperation External Evaluation Report. (2007).
- 698 83. Mulder, J. P. M., Hommes, S. & Horstman, E. M. Implementation of coastal erosion
699 management in the Netherlands. *Ocean Coast. Manag.* **54**, 888–897 (2011).
- 700 84. Elias, E. P. L. & Van Der Spek, A. J. F. Dynamic preservation of Texel Inlet, the Netherlands:
701 Understanding the interaction of an ebb-tidal delta with its adjacent coast. *Geol. en*
702 *Mijnbouw/Netherlands J. Geosci.* **96**, 293–317 (2017).
- 703 85. Mehvar, S., Filatova, T., Dastgheib, A., de Ruyter van Steveninck, E. & Ranasinghe, R.
704 Quantifying Economic Value of Coastal Ecosystem Services: A Review. *J. Mar. Sci. Eng.* **6**, 5
705 (2018).
- 706 86. Reguero, B. G., Beck, M. W., Agostini, V. N., Kramer, P. & Hancock, B. Coral reefs for coastal
707 protection: A new methodological approach and engineering case study in Grenada. *J. Environ.*
708 *Manage.* **210**, 146–161 (2018).
- 709 87. Harris, D. L. *et al.* Coral reef structural complexity provides important coastal protection from
710 waves under rising sea levels. *Sci. Adv.* **4**, 1–8 (2018).
- 711 88. Heron, S. F. *et al.* Impacts of Climate Change on World Heritage Coral Reefs: A First Global
712 Scientific Assessment. *Paris, UNESCO World Herit. Centre.* 1–14 (2017).
- 713 89. Hoegh-Guldberg, O. *et al.* *Impacts of 1.5°C of Global Warming on Natural and Human Systems.*
714 https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter3_Low_Res.pdf
715 (2018).
- 716 90. Hoegh-guldberg, O., Kennedy, E. V., Beyer, H. L., McClennen, C. & Possingham, H. P. Securing a
717 Long-term Future for Coral Reefs. *Trends Ecol. Evol.* **33**, 936–944 (2018).
- 718 91. Zaneveld, J. R. *et al.* Overfishing and nutrient pollution interact with temperature to disrupt
719 coral reefs down to microbial scales. *Nat. Commun.* **7**, 1–12 (2016).
- 720 92. Richards, J. A. & Richards, J. A. Error Correction and Registration of Image Data. *Remote Sens.*
721 *Digit. Image Anal.* 39–74 (1993) doi:10.1007/978-3-642-88087-2_2.
- 722 93. Zheng, X., Huang, Q., Wang, J., Wang, T. & Zhang, G. Geometric accuracy evaluation of high-
723 resolution satellite images based on Xianning test field. *Sensors (Switzerland)* **18**, 1–11 (2018).
- 724 94. Cazenave, A. & Cozannet, G. Le. Sea level rise and its coastal impacts. *Earth's Futur.* **2**, 15–34
725 (2013).
- 726 95. Pickering, M. D. *et al.* The impact of future sea-level rise on the global tides. *Cont. Shelf Res.*
727 **142**, 50–68 (2017).

728 96. Leatherman, S. P., Zhang, K. & Douglas, B. C. Sea level rise shown to drive coastal erosion. *Eos*
729 *(Washington, DC)*. **81**, 55–57 (2000).

730 97. De Jong, F. *et al.* Wadden Sea Quality Status Report - Geomorphology. *Wadden Sea Ecosyst.* **9**,
731 (1999).

732 98. Nicholls, R. J. Assessing erosion of sandy beaches due to sea-level rise. *Geol. Soc. Eng. Geol.*
733 *Spec. Publ.* **15**, 71–76 (1998).

734 99. Le Cozannet, G., Garcin, M., Yates, M., Idier, D. & Meyssignac, B. Approaches to evaluate the
735 recent impacts of sea-level rise on shoreline changes. *Earth-Science Rev.* **138**, 47–60 (2014).

736 100. Reise, K. Coast of change: Habitat loss and transformations in the Wadden Sea. *Helgol. Mar.*
737 *Res.* **59**, 9–21 (2005).

738 101. Benninghoff, M. & Winter, C. Recent morphologic evolution of the German Wadden Sea. *Sci.*
739 *Rep.* **9**, 1–9 (2019).

740 102. Lotze, H. K. *et al.* Human transformations of the Wadden Sea ecosystem through time: A
741 synthesis. *Helgol. Mar. Res.* **59**, 84–95 (2005).

742 103. Becherer, J. *et al.* The Wadden Sea in transition - consequences of sea level rise. *Ocean Dyn.*
743 **68**, 131–151 (2018).

744 104. Perry, J. Climate change adaptation in natural world heritage sites: A triage approach. *Climate*
745 **7**, (2019).

746 105. Bottrill, M. C. *et al.* Is conservation triage just smart decision making? *Trends Ecol. Evol.* **23**,
747 649–654 (2008).

748 106. Salm, R. V. & Clark, J. R. *Marine and Coastal Protected Areas: A guide for Planners and*
749 *Managers.* (2010).

750