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Sandy coastlines under threat of erosion

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# **1. Extended Data**

Figure #	Figure title	Filename	Figure Legend
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		Smith_ED_Fi_1.jpg	
Extended Data Fig. 1	Geographical regions considered in the present analysis	Vousdoukas_E D_01.eps	Geographical regions considered in the present analysis, based on the IPCC SREX report and limited to those that contain ice- free sandy coastlines
Extended Data Fig. 2	Projected long term shoreline change due to SLR driven retreat (R) alone, by the year 2050 and 2100 under RCP4.5 and RCP8.5.	Vousdoukas_E D_02.eps	Projected long term shoreline change due to SLR driven retreat (R) alone, by the year 2050 (a,c) and 2100 (b,d) under RCP4.5 (a- b) and RCP8.5 (c-d). Values represent the median change and positive/negative values express accretion/erosion in m, relative to 2010. The global average median change is shown in the inset text for each case, along with the 5 <sup>th</sup> -95 <sup>th</sup> percentile range.
Extended Data Fig. 3	Projected long term shoreline change driven due to the ambient shoreline change rate (AC) alone, by the year 2050 and 2100.	Vousdoukas_E D_03.eps	Projected long term shoreline change driven due to the ambient shoreline change rate (AC) alone, by the year 2050 (a) and 2100 (b). Values represent the median change and positive/negative values express accretion/erosion in m, relative to 2010. The global average median change is shown in the inset text for each case, along with the 5 <sup>th</sup> -95 <sup>th</sup> percentile range.
Extended Data Fig. 4	Projected change in 100-year episodic beach erosion for the year 2050 and 2100 under RCP4.5 and	Vousdoukas_E D_04.eps	Projected change in 100-year episodic beach erosion for the year 2050 (a,c) and 2100 (b,d) under RCP4.5 (a-b) and RCP8.5 (c-d). Values represent the median change and positive/negative values express less/more erosion (m), relative to 2010. The global average median change is shown in

	RCP8.5.		the inset text for each case, along with the 5 <sup>th</sup> -95 <sup>th</sup> percentile range.
Extended Data Fig. 5	Projected median long term shoreline change under RCP4.5 by the year 2050 (dx <sub>shore,LT</sub> ), for the 26 IPCC SREX sub- regions and the worldwide average	Vousdoukas_E D_05.eps	Projected median long term shoreline change under RCP4.5 by the year 2050 (dx <sub>shore,LT</sub> ), for the 26 IPCC SREX sub- regions and the worldwide average (horizontal bar plot; positive/negative values express accretion/erosion in m). Shoreline change is considered to be the result of SLR retreat (R) and ambient shoreline change trends (AC). Pie plots show the relative contributions of R and AC to the projected median dx <sub>shore,LT</sub> , with transparent patches expressing accretive trends. Vertical bar plots show the relative contributions of R and AC, as well as that of RCPs, to the total uncertainty in projected median dx <sub>shore,LT</sub> .
Extended Data Fig. 6	Projected median long term shoreline change under RCP8.5 by the year 2050 (dx <sub>shore,LT</sub> ), for the 26 IPCC SREX sub- regions and the worldwide average	Vousdoukas_E D_06.eps	Projected median long term shoreline change under RCP8.5 by the year 2050 ( $dx_{shore,LT}$ ), for the 26 IPCC SREX sub- regions and the worldwide average (horizontal bar plot; positive/negative values express accretion/erosion in m). Shoreline change is considered to be the result of SLR retreat (R) and ambient shoreline change trends (AC). Pie plots show the relative contributions of R and AC to the projected median $dx_{shore,LT}$ , with transparent patches expressing accretive trends. Vertical bar plots show the relative contributions of R and AC, as well as that of RCPs, to the total uncertainty in projected median $dx_{shore,LT}$ .
Extended Data Fig. 7	Projected median long term shoreline change under RCP4.5 by the year 2100 (dx <sub>shore,LT</sub> ), for the 26 IPCC SREX sub- regions and the worldwide average	Vousdoukas_E D_07.eps	Projected median long term shoreline change under RCP4.5 by the year 2100 (dx <sub>shore,LT</sub> ), for the 26 IPCC SREX sub- regions and the worldwide average (horizontal bar plot; positive/negative values express accretion/erosion in m). Shoreline change is considered to be the result of SLR retreat (R) and ambient shoreline change trends (AC). Pie plots show the relative contributions of R and AC to the projected

			median dx <sub>shore,LT</sub> , with transparent patches expressing accretive trends. Vertical bar plots show the relative contributions of R and AC, as well as that of RCPs, to the total uncertainty in projected median dx <sub>shore,LT</sub> .
Extended Data Fig. 8	Percentage length of sandy beach shoreline that is projected to retreat by more than 50, 100 and 200 m per IPCC SREX sub-region	Vousdoukas_E D_08.eps	Bar plots showing, per IPCC SREX sub- region, the percentage length of sandy beach shoreline that is projected to retreat by more than 50 (blue), 100 (yellow) and 200 m (red), by 2050 (a,c) and 2100 (b,d), under RCP4.5 (a-b) and RCP8.5 (c-d) relative to 2010. Transparent color patches indicate the 5 <sup>th</sup> -95 <sup>th</sup> quantile range and solid rectangles show the median value. For the region abbreviations, please see Extended Data Fig. 1.
Extended Data Fig. 9	Length of sandy beach shoreline that is projected to retreat by more than 50, 100 and 200 m per IPCC SREX sub-region	Vousdoukas_E D_09.eps	Bar plots showing, per IPCC SREX sub- region, the length (in km) of sandy beach shoreline that is projected to retreat by more than 50 (blue), 100 (yellow) and 200 m (red), by 2050 (a,c) and 2100 (b,d), under RCP4.5 (a-b) and RCP8.5 (c-d) relative to 2010. Transparent color patches indicate the 5 <sup>th</sup> -95 <sup>th</sup> quantile range and solid rectangles show the median value. For the region abbreviations, please see Supplementary Figs. S2 and S5
Extended Data Fig. 10	Per country length of sandy beach shoreline that is projected to retreat by more than 100 m	Vousdoukas_E D_10.eps	Per country length of sandy beach coastline which is projected to retreat by more than 100 m by 2050 (a,c) and 2100 (b,d), under RCP4.5 (a-b) and RCP8.5 (c-d). Values are based on the median long term shoreline change, relative to 2010.

# **3 2. Supplementary Information:**

- 4 A. Flat Files
- 5

Item	Present?	Filename	A brief, numerical description of file
		This should be the	contents.

		name the file is saved as when it is uploaded to our system, and should include the file extension. The extension must be .pdf	i.e.: Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.
Supplementary	Yes	Vousdoukas_NLe	Supplementary Figure 1, Supplementary Tables 1-4.
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# 8 B. Additional Supplementary Files

Туре	Number If there are multiple files of the same type this should be the numerical indicator. i.e. "1" for Video 1, "2" for Video 2, etc.	Filename This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. i.e.: <i>Smith_</i> <i>Supplementary_Video_1.mov</i>	Legend or Descriptive Caption Describe the contents of the file
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# **3. Source Data**

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Parent Figure or	Filename	Data description
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	Unmodified_Gels_Fig1.pdf	
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# <sup>15</sup> Sandy coastlines under threat of erosion

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- 35

Sandy beaches occupy more than one third of the global coastline<sup>1</sup> and have high socio-36 economic value related to recreation, tourism, and ecosystem services<sup>2</sup>. Beaches are the interface 37 between land and ocean, providing coastal protection from marine storms and cyclones<sup>3</sup>. However 38 the presence of sandy beaches cannot be taken for granted, as they are under constant change, driven 39 by meteorological<sup>4,5</sup>, geological<sup>6</sup>, and anthropogenic factors<sup>1,7</sup>. A substantial proportion of the world's 40 sandy coastline is already eroding<sup>1,7</sup>, a situation that could be exacerbated by climate change<sup>8,9</sup>. Here, 41 42 we show that with, climate mitigation, ambient trends in shoreline dynamics, combined with coastal 43 recession driven by sea level rise could result in the near extinction of almost half of the world's sandy 44 beaches by the end of the century. Moderate greenhouse gas emission mitigation could prevent 40% 45 of shoreline retreat. Projected shoreline dynamics are dominated by sea level rise for the majority of 46 sandy beaches, but in certain regions this is overshadowed by ambient shoreline changes. In West and East Asia, long-term accretion up to 200-300 m is projected. A significant proportion of the threatened 47 sandy shorelines are in densely populated areas, underlining the need for the design and 48 49 implementation of effective adaptive measures.

50

The coastal zone is among the most developed areas worldwide, containing an abundance of developments, critical infrastructure<sup>10</sup>, and ecosystems<sup>2,3</sup>. As a result, population density tends to be higher near the coast<sup>11</sup>, and most projections indicate that current trends of coastward migration, urbanization and population growth will continue<sup>12,13</sup>. Of the different beach typologies found worldwide sandy beaches are the most heavily utilized<sup>14</sup> and are among the most geomorphologically complex, with the shoreline, i.e. the mean water line along the coast, changing constantly under forcingresponse interactions between natural and anthropogenic factors<sup>7</sup>. The global mean sea level has been increasing at an accelerated rate during the past 25 years<sup>15</sup> and will continue to do so in view of climate change<sup>16,17</sup>. While shoreline change can be the combined result of a wide range of potentially erosive or accretive factors<sup>8</sup>, there is a clear cause and effect relation between increasing sea levels and shoreline retreat<sup>18</sup>, pointing to increased coastal erosion issues<sup>9,19</sup>. Climate change will also affect waves and storm surges<sup>20,21</sup>, which are important drivers of coastal morphology<sup>4,5,22</sup>, and therefore considering the dynamics of extreme weather patterns is also important in assessing potential climate change impacts beyond that of SLR alone.

Here we present a comprehensive global analysis of sandy shoreline dynamics during the 21<sup>st</sup> century. 65 Our probabilistic projections explicitly take into account estimates of future SLR, spatial variations of 66 67 coastal morphology, ambient shoreline change trends, and future changes in meteorological drivers (e.g. 68 storm surge and waves). We first evaluate long term shoreline change  $dx_{shore LT}$ , which is the result of two components: the ambient shoreline change (AC) driven by geological, anthropogenic and other 69 physical factors<sup>7</sup> and the shoreline retreat due to SLR (R) (Supplementary Fig. S1). We obtained AC by 70 extrapolating observed historical trends<sup>7</sup> within a probabilistic framework (see Methods). We computed 71 R by using a modified Bruun rule<sup>18</sup> together with a new global dataset of active beach slopes<sup>23</sup>. In 72 73 addition to the long term shoreline dynamics we also project how maximum erosion from coastal 74 storms may change in view of climate change. Shoreline change projections are discussed for the years 2050 and 2100 under RCP 4.5 and 8.5, relative to the baseline year 2010. 75

76 Our analysis shows an overall erosive trend of sandy beaches that increases in time and with the 77 intensity of greenhouse gas emissions (Figure 1). Assuming that there are no physical limits in potential retreat, by mid-century we project a very likely (5-95<sup>th</sup> percentile) global average long term shoreline 78 79 change dx<sub>shore1T</sub> ranging from -2.2 to -79.2 m and -0.8 to -99.2 m,, under RCP4.5 and RCP8.5, respectively 80 (negative values express erosion; Supplementary Table S1). By the end of the century the erosive trend 81 becomes even more dominant and we project a very likely range from -21.7 to -171.1 m and -42.2 to -82 246.9 m under RCP4.5 and RCP8.5, respectively (Figure 2 Supplementary Table S1). Moderate 83 greenhouse gas emission mitigation could thus prevent 22% of the projected shoreline retreat by 2050 84 and 40% by the end of the century (Supplementary Table S1). This corresponds to a global average of around 42 m of preserved sandy beach width by the end of the century. 85

The global erosive trend masks high spatial variability, with erosive and accretive tendencies interchanging across regions and along nearby coastal segments (Figure 1). Whereas local trends can exceed several meters per year, eight IPCC sub-regions show median retreats exceeding 100 m under both RCPs by the end of the century (Supplementary Table S1; see Figure 2 for a definition of the regions): East North America, Amazon, Southeastern South America, Central Europe, South and West Asia, North Australia, and the Caribbean SIDS. By 2100,  $dx_{\text{shore,LT}}$  exceeds 150 m under RCP8.5 in all the above regions, while under the same scenario median retreats larger than 300 m are projected for South Asia and the Caribbean SIDS. Long term accretion is projected along sandy coastlines of East Asia under both RCPs by 2050 and only under RCP4.5 by the end of the century.

95 SLR driven retreat R is responsible for 71% and 75% of the global median shoreline change in 2050 under 96 RCP4.5 and RCP8.5, respectively (Extended data Figs 5-6); and for 86% and 77% by the end of the 97 century (Figure 2 and Extended Data Fig. 7). Ambient shoreline changes dominate only in certain 98 regions, in particular in South and West Asia, West Indian Ocean, Southeastern South America, and the 99 Caribbean SIDS regions. The contributions of the SLR retreat and ambient change to the overall 100 uncertainty under RCP4.5 and by mid-century are relatively balanced (Extended Data Fig. 5), while AC 101 contributes to 41% more uncertainty globally, by the end of the century (Extended Data Fig. 7). Under 102 RCP8.5 uncertainty related to SLR retreat dominates that of AC, by 44% and 30%, by the years 2050 and 103 2100, respectively (Extended Data Fig. 7 and Figure 2). Regionally, ambient change uncertainty is higher 104 in North Australia South Asia.

The above estimates do not include the episodic, storm-driven shoreline retreat S, presently projected 105 using the convolution erosion model of Kriebel and Dean<sup>24</sup> (see Methods). Here we discuss the 100-year 106 107 event S which for the year 2050 is equivalent to circa 23% of the global average projected long term shoreline change  $dx_{\text{shore,LT}}$  (Supplementary Tables S1-4). By the end of the 21<sup>st</sup> century, the relative 108 109 importance of the 100-year S compared to  $dx_{\text{shore,LT}}$  decreases to 9% and 7% under RCP4.5 and 8.5, 110 respectively, as long term changes gather pace. Storm erosion is typically followed by beach recovery<sup>25</sup>, but some events may leave a footprint that takes decades to recover, if at all<sup>4,26</sup>, while the additional 111 112 shoreline retreat renders the backshore more vulnerable to episodic coastal flooding and its 113 consequences. Despite previous studies projecting changes in wave intensity and direction worldwide<sup>21,27,28</sup>, our projections show that overall climate change will not have a strong effect on 114 115 episodic storm driven erosion. As a result, ambient and SLR driven change appear to shadow the effect 116 of changes in storm-driven erosion, even though at certain locations  $\Delta S$  values can reach ±20 m by the 117 end of the century; e.g. increase in 100-year erosion potential along the South East UK, West coast of Germany, North Queensland (Australia), and Acapulco (Mexico) (Extended Data Fig. 4). 118

119 The projected shoreline changes will substantially impact on the shape of the world's coastline. Many coastal systems have lost already their natural capacity to accommodate or recover from erosion, as the 120 backshore is heavily occupied by human settlements<sup>29</sup>, while dams and human development have 121 depleted terrestrial sediment supply which would naturally replenish the shore with new material<sup>30,31</sup>. 122 123 Most of the remaining regions with an extensive presence of a natural coastline, are found in Africa and 124 Asia, which are also the regions projected to experience the highest coastal population and urbanization growth in the decades to come<sup>12,13</sup>. There is yet no global dataset on sandy beach width allowing to 125 126 accurately estimate the potential loss of sandy beaches around the world. Therefore, to quantify the 127 potential impact of our projections, we consider beaches that are projected to experience a shoreline 128 retreat >100 m as seriously threatened by coastal erosion. The chosen 100 m threshold is rather 129 conservative, since most sandy beaches have widths below 50 m, especially near human settlements, 130 small islands and micro-tidal areas (e.g. Caribbean, Mediterranean).

We find that 10.6%-12.2% (28,260-32,456 km) of the world's sandy beaches could face severe erosion by 2050 and 37.2%-50.9% (99,996-135,279 km) by the end of the century (Extended Data Fig. 8). Thirty one percent (31%) of the world's sandy beaches are in low elevation coastal zones (LECZ) with population density exceeding 500 people per km<sup>2</sup>, and our projections show that approximately one third of these LECZ sandy coasts will be seriously threatened by erosion by the year 2050. This estimate reaches 51% and 62% by the end of the century, under RCP4.5 and RCP8.5, respectively.

Several countries could face extensive erosion by the end of the 21<sup>st</sup> century (along >80% of their sandy 137 coastline under both RCPs; Figure 3) including Democratic Republic of the Congo, Gambia, Jersey, 138 139 Suriname, Comoros, Palau, Benin, Guinea-Bissau, Mayotte, Iraq, Pakistan, Guinea and El Salvador. Apart 140 from the consequent higher vulnerability to coastal hazards, several of these countries are likely to 141 experience substantial socioeconomic implications as their economies are fragile and, tourism-142 dependent with sandy coastlines constituting their major tourist attraction. When the total length of 143 sandy beaches projected to be lost by 2100 is considered (as opposed to the %), Australia emerges as the 144 potentially most affected country, with at least 12,324 km of sandy beach coastline threatened by 145 erosion (15,439 under RCP8.5; Extended Data Fig. 9), circa 40% of the country's total sandy coastline. By 146 the same impact metric, Canada ranks second (9,577 and 16,651 km 15,439 under RCP4.5 and RCP8.5, 147 respectively), followed by Chile (5,471 and 7,050 km), Mexico (4,119 and 5,105 km) China (4,084 and 5,185 km), USA (3,908 and 5,553 km), Argentina (3,668 and 4,413 km) and Iran (3,654 and 3,870 km). 148

Past experience has shown that effective site-specific coastal planning can mitigate beach erosion, eventually resulting in a stable coastline; with the most prominent example being the Dutch coast<sup>32</sup>. A positive message from the present analysis is that while SLR will drive shoreline retreat almost everywhere, many locations show ambient erosive trends related to human interventions<sup>7</sup>, which in theory could be avoided by more sustainable coastal zone and catchment management practices. At the same time, the range of projected SLR implies unprecedented pressure to our coasts which requires the development and implementation of informed and effective adaptive measures.

## 156 CORRESPONDENCE

157 Correspondence and requests for materials should be addressed to M.I.V.

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#### **Figure captions** 242

243 Figure 1. Projected long term shoreline change. By the year 2050 (a,c) and 2100 (b,d) under RCP4.5 (a-b) and RCP8.5 (c-d).

- 244 Values represent the median change and positive/negative values respectively express accretion/erosion in m, relative to 2010.
- 245 The global average median change is shown in the inset text for each case, along with the 5th-95th percentile range.

246

- 247 Figure 2. Projected median long term shoreline change under RCP8.5 by the year 2100 (dx<sub>shore,LT</sub>), for the 26 IPCC SREX sub-248 regions and the worldwide average. For the horizontal bar plot on right; positive/negative values express accretion/erosion in m;
- 249 black error bars indicate the  $5^{th}$ - $95^{th}$  quantile range. Shoreline change is considered to be the result of SLR retreat (R) and
- 250
- ambient shoreline change trends (AC). Pie plots show the relative contributions of R and AC to the projected median  $dx_{shore,LT}$  with transparent slices expressing accretive trends. Vertical bar plots show the ratio between the uncertainty of R and AC (5<sup>th</sup>-251
- 252  $95^{th}$  quantile range), to the total uncertainty in projected median  $dx_{shore,LT}$ .

253

- 254 Figure 3. Per country percentages of the sandy coastline length which is projected to retreat by more than 100 m. By 2050 (a,c)
- 255 and 2100 (b,d), under RCP4.5 (a-b) and RCP8.5 (c-d). Values are based on the median long term shoreline change, relative to
- 256 2010.

257

258 1 Methods

#### **259** 1.1 General concepts

In this study we project shoreline dynamics throughout this century along the world's sandy coastlines under two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be viewed as a *moderate-emission-mitigation-policy scenario* and RCP8.5 as a *high-emissions scenario*<sup>33</sup>. The study focusses on the evolution of three components of sandy beach shoreline dynamics (Supplementary Fig. S1):

- AC: Ambient shoreline dynamics driven by long-term hydrodynamic, geological and anthropic
   factors.
- 267 *R*: Shoreline retreat due to coastal morphological adjustments to Sea Level Rise (SLR).

269 The first two components represent longer term shoreline changes and are quantified here as:

$$dx_{shore\,LT} = AC + R \tag{1}$$

271 AC expresses long-term ambient shoreline dynamics that can be driven by a wide range of natural 272 and/or anthropogenic processes, excluding the effect of SLR (R) and that of episodic erosion during 273 extreme events (S; see following paragraph). In most cases AC is related to human interventions that alter the sediment budget and/or transport processes of coastal systems<sup>7</sup>, but it also includes natural 274 transitions due to a variety of reasons, such as weather patterns<sup>4,34-36</sup>, persistent longshore transport 275 variations<sup>37</sup>, or geological control<sup>38,39</sup>.*R* in Eq. 1 represents SLR-driven shoreline retreat, the magnitude 276 of which depends on the transfer of sediment from the sub-aerial to the submerged part of the active 277 278 beach profile, in order to adjust to rising Mean Sea Levels (MSLs).

The third component *S* represents episodic erosion from intense waves and storm surges during extreme weather events. Episodic erosion is usually followed by a recovery process<sup>40-42</sup>. It is assumed here that the irreversible net effect of episodic erosion and post-storm recovery constitutes part of the ambient shoreline evolution expressed by *AC*. *S* is therefore limited to the reversible episodic shoreline retreat during storm events relative to its long term position expressed by  $dx_{shore,LT}$ . Potential variations in storminess with global warming will induce changes in *S* compared to present day conditions. At any point in time, the maximum shoreline retreat  $dx_{shore,max}$  during an extreme coastal event due to the combined effects of long-term and episodic erosion is then defined as

$$dx_{shore.max} = AC + R + S$$

2

288 Each of these components are discussed in more detail below.

This study focuses on ice-free sandy beaches, which constitute the most common and dynamic beach type globally, covering more than 30% of the ice-free coastline in the world<sup>1,43</sup>. While in reality shoreline retreat can be limited by the presence of natural or anthropogenic barriers, spatial data on such features is not available globally at the resolution needed for the present study. Adaptive measures against beach erosion could have a similar effect, but are difficult to predict and merit a separate study. Therefore, we do not invoke any physical limits to the extent of potential shoreline retreat.

#### **295** 1.2 Ambient shoreline dynamics

Several parts of the global coastline undergo long-term ambient changes as a result of various 296 297 hydrodynamic, geological and anthropic factors. Historical shoreline trends were estimated by Mentaschi et al.<sup>7</sup> from the high-resolution Global Surface Water (GSW) database<sup>44</sup>. It provides spatio-298 299 temporal dynamics of surface water presence globally at 30 m resolution from 1984 to 2015, obtained 300 by the automated analysis of over 3 million Landsat satellite images. This GSW dataset was processed 301 for changes in water presence in coastal areas to produce time series of cross-shore shoreline position'. 302 The pixel-wise information of GSW was translated into cross-shore shoreline dynamics using a set of 303 over 2,000,000 shore-normal transects. The transects were defined every 250 m along a global coastline obtained from OpenStreetMap<sup>45</sup> and were sufficiently long to accommodate the shoreline displacement 304 305 during the study period. Each transect defines a 200 m alongshore-wide coastal section, along which 306 surface water transitions were considered in order to extract time-series of shoreline displacement 307 along each shore normal transect.

We consider as a proxy for the shoreline change the cross-shore displacement of the seaward boundary of the 'permanent land layer'; i.e. the areas where water presence has never been detected throughout the year. Over the 32-year period considered, the selected proxy can respond to tidal, storm surge, wave and swash dynamics, as well as the inter-related dynamics of the beach face slope or nearshore bathymetry. Among the different shoreline definitions proposed in literature<sup>46</sup>, the present one was chosen as it is more compatible with the type of analysis and the spatial and temporal resolution of the satellite dataset<sup>46</sup>. A detailed description of the procedure, the data, and also links to the final dataset can be found in Pekel et al.<sup>44</sup>, and Mentaschi et al.<sup>7</sup>.

For the purpose of determining AC in the present study, we consider shoreline dynamics data for a 32-316 year period (1984-2015) from Mentaschi et al.<sup>7</sup>. We assume that this time series is representative for 317 present-day ambient shoreline changes and extrapolate the trend into the future using a probabilistic 318 319 approach. For each location, we consider the time series of all transects that are within 5 km distance 320 along the same coastline stretch. This acts as a spatial smoothing in order to filter out local trends and 321 reflects changes at km scale, which are more relevant in a global scale analysis. It further ensures that 322 each transect has sufficient data and compensates for gaps in the satellite measurements due to poor 323 quality or lack of data. The original dataset comes with confidence indicators and low-confidence 324 measurements are excluded from the analysis. Similarly, shoreline changes that exceed 5 km in a year 325 are also excluded as outliers.

326 The above analysis results in sets of annual shoreline displacements for each point, which are sampled 327 randomly to generate synthetic series of future shoreline position with an annual time step. The Monte 328 Carlo sampling results in one million realizations of future shoreline evolution, resulting in Probability 329 Density Functions (PDFs) of annual shoreline displacement during the present century in each transect. 330 The number of realizations was taken to ensure a stable PDF of the shoreline changes by the end the century in all studied transects, i.e. when the mean and the standard deviation of the PDFs converged. 331 332 The realizations of future shoreline evolution assume that ambient change will follow historical trends 333 and express the uncertainty of the historical observations.

#### **334** 1.3 Shoreline retreat due to SLR

The estimation of the equilibrium shoreline retreat *R* of sandy coasts due to SLR is based on the Bruun rule<sup>18</sup>. This approach builds on the concept that the beach morphology tends to adapt to the prevailing wave climate and is given by:

338

$$R = \frac{1}{\tan\beta} SLR \tag{3}$$

339

340 where  $\tan \theta$  is the active profile slope.

Projections of regional SLR up to the end of this century are available from a probabilistic, process-based
 approach<sup>47</sup> that combines the major factors contributing to SLR: impact of self-attraction and loading of

the ocean upon itself due to the long term alteration of ocean density changes, globally averaged steric sea-level change, dynamic sea-level change, surface mass balance of ice from glaciers and ice-caps, surface mass balance and ice dynamics of Greenland and Antarctic ice sheet, land-water storage and Glacial Isostatic Adjustment. Local smaller scale vertical land movements such as land subsidence due to for example ground water pumping are not included in the SLR projections.

348 The tan $\theta$  term in equation 3 expresses the slope of the active beach profile, which to date typically has been assumed to be constant (in space) in large scale studies<sup>9</sup>. Here, we use a newly released global 349 350 dataset of active beach slopes<sup>23</sup>. The dataset has been created combining the MERIT digital elevation dataset<sup>48</sup> with the GEBCO bathymetry<sup>49</sup>. Beach profiles are generated along each sandy beach transect 351 352 by combining the above bathymetric and topographic data. The offshore boundary of the active profile is defined by the furthest location from the coast with a depth equal to the depth of closure  $d_c$ . The 353 latter is calculated using an adaptation of the original Hallermeier 1978<sup>50</sup> formula byNicholls et al. 1998<sup>51</sup> 354 355 for applications on longer time scales, given by:

356

$$d_c = 2.28H_{e,t} - 68.5 \left(\frac{H_{e,t}^2}{gT_{e,t}^2}\right)$$
4

where  $H_{e,t}$  is the significant wave height that is exceeded only 12 hours per *t* years,  $T_{e,t}$  is the associated wave period, and *g* is the gravitational acceleration. In this case *t* is equivalent to the 1980-2100 period.

The landward active profile boundary varies among studies and has been defined as the crest of the berm or dune, or the most offshore location with an elevation equal to the MSL. In the absence of reliable estimates of the dune or berm height *B*, and following the original definition of the Bruun Rule<sup>18</sup> and its application in several recent studies<sup>9,52,53</sup>, here we take the MSL contour as the landward active profile boundary. The cross-shore distance between these two points is considered as the length of the active profile  $L_b$ , of which the slope is defined as  $tan\beta = \frac{d_c}{L_b}$ .

Waves are simulated over the period 1980 to 2100 using the third generation spectral wave model 365 WAVEWATCH-III forced by atmospheric conditions from 6 CMIP5 GCMs<sup>28,54</sup>. The model runs on a global 366  $1.5^{\circ}$  grid, combined with several nested finer sub-grids with resolution varying from  $0.5^{\circ}$  to  $0.5^{\circ}$ . The 367 368 model's skill to reproduce global wave fields was assessed by comparing time series form a reanalysis covering 35 years between 1980 and 2014, forced by ERA-Interim wind data, against altimeter data 369 provided by 6 different satellites<sup>55</sup>: ERS-2, ENVISAT, Jason 1 and 2, Cryosat 2 and SARAL-AltiKa. Point 370 371 measurements provided by buoys were used for additional validation. Detailed information on the model set-up and validation can be found in the references provided<sup>28,54</sup>. 372

Several recent studies in Australia<sup>41</sup>, Netherlands<sup>56</sup>, Spain<sup>57</sup> and France<sup>58</sup> that compared coastline retreat projections obtained via the physics based Probabilistic coastline recession (PCR) modelwith those derived with the Bruun rule have indicated that the latter consistently provides higher-end estimates of coastline retreat. Acknowledging that the extent of overestimation depends on site-specific factors, we therefore include in our probabilistic framework a correction factor *E*, which varies randomly between 0.1 and 1.0 centered around a conservative median value 0.75. Thus, here we compute SLR driven shoreline retreat using the equation:

$$R = E \cdot \frac{1}{\tan\beta} \cdot SLR$$
 5

Finally, the active beach slope analysis detected that tan*θ* values in some parts of the world can be as mild as 1/800. According to the Bruun rule and the projected range of SLR, such mild sloping coastal zones will experience shoreline retreats of several hundreds of meters. While not impossible, such estimates could yield serious potential overestimations of real-world shoreline adjustment to SLR<sup>59</sup>. We therefore limit the minimum beach slope to 1/300, which is a realistic lower bound estimate for sandy beaches.

As SLR retreat is estimated in a probabilistic manner through Monte Carlo simulations, the resulting
 PDFs express the uncertainty from the SLR projections and the Bruun rule error expressed through the E
 correction factor.

#### **390** 1.4 Storm-induced erosion

Episodic erosion during extreme storms is estimated using the convolution erosion model KD93 of Kriebel and Dean<sup>24</sup>. KD93 is based on the equilibrium profile concept and estimates shoreline retreat and volumetric sand loss due to extreme waves and storm surge. KD93 input can be classified in (i) hydrodynamic variables: significant wave height ( $H_s$ ), peak wave period ( $T_p$ ), wave incidence angle ( $\alpha_w$ ), storm surge ( $\eta_s$ ), tidal level ( $\eta_{tide}$ ) and event duration; and (ii) parameters related to the beach profile: dune height *D*, berm height *B* and width W, and the beach-face slope tan $\beta_f$ .

397 Storm surges for the present and future climate conditions are simulated using the DFLOW FM 398 model<sup>60,61</sup> forced with the same 6-member CMIP5 Global Climate Model (GCM) ensemble as the wave 399 projections<sup>20</sup> (described in the previous section).

400 The hydrodynamic conditions driving episodic beach erosion are obtained from the wave and storm 401 surge projections. For each of the 6 GCMs we extracted the storm events simulated during the period 402 1980-2100, considering the parameters: max  $H_{sr}$   $\eta_s$ ,  $\eta_{tide}$  and  $T_{pr}$ , as well as mean wave direction *Dir*<sub>w</sub>, and 403 event duration. The extraction of storm events is based on the following criteria: (i) maximum  $H_s$  or  $\eta_s$ 404 exceeding the 90<sup>th</sup> percentile value; (ii) maximum  $T_p$  above 3 s; and (iii) maximum  $H_s$  above 0.5 m.

The offshore wave conditions are transformed to the nearshore(50 m depth) through wave refraction, shoaling and breaking calculations based on Snell's law, following the approach described in Part II, Chapter 2 of the US Army Corps Coastal engineering Manual<sup>62</sup>. The wave incidence angle required for the calculations is obtained by combining the wave direction of each event from the model output with the mean shoreline orientation. The active beach slope is obtained from the global dataset mentioned above<sup>23</sup>.

Subsequently, we simulate storm induced erosion for all the above events using KD93 on equilibrium profiles, obtaining a sequence of shoreline retreat events for each transect. Subsequently, we apply non-stationary extreme value statistical analysis<sup>63</sup> and fit a generalized Pareto distribution to the retreat event series in order to obtain shoreline retreat estimates for different return periods. The present analysis focuses on the storm-induced shoreline retreat for the 100-year retreat event S<sub>100</sub>, and its difference ( $\Delta$ S<sub>100</sub>) compared to present day conditions.

As storm retreat is estimated in a probabilistic manner through Monte Carlo simulations, the resulting
PDFs express the uncertainty from the wave projections (i.e. GCM ensemble spread and ocean model
error).

#### 420 1.5 Spatial analysis

The study focusses on sandy beaches along the global coastline, which have been detected in a recent study by discretizing the coast at 500 m alongshore transects<sup>1</sup>. We use the Global Human Settlement Layer<sup>64</sup> to estimate the population in low-lying coastal areas (i.e. elevation <10 m MSL) within a distance of 25 km from each sandy beach transect. This serves as a proxy for the number of people benefiting from nearby sandy beaches; either receiving natural protection from coastal storms, or benefiting from beach amenity value, or other socio-economic activities related to tourism, beach-use, etc.

In order to identify regional patterns in shoreline dynamics, the global coastline is divided in 26 geographical regions (Extended Data Fig. 1), as defined in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation<sup>65</sup>. The values discussed in the manuscript correspond to averages for each region and country, or for the entire global coastline.

#### **431** 1.6 Statistical analysis

432 Equations 1 and 2 are applied here in a probabilistic manner, with the assumption that shoreline change 433 components R, S and AC are independent. PDFs of the three components are combined through Monte Carlo simulations following the steps below<sup>20</sup>: (i) random sampling from the individual PDFs; (ii) linear 434 addition of the  $dx_{shore}$  components according to equations 1 and 2; (iii) control of convergence to ensure 435 436 that the number of realizations is sufficient; (iv) joint PDF estimation. Typically one million realizations 437 are sufficient to obtain stable PDFs and convergence of the final percentiles. The resulting PDF of  $dx_{shore}$ 438 expresses the joint contributions from all components and the uncertainty therein (uncertainty factors 439 considered for each component are discussed in the final paragraph of the different dedicated sections 440 1.2-1.4).

We express the relative contribution of a component by the fraction of its median value to the median total retreat. Similarly, relative contributions to the total  $dx_{shore}$  uncertainty is expressed by the fraction of each component's variance to the total variance. We also estimate the difference between the median  $dx_{shore}$  values for RCP4.5 and RCP8.5.

#### 445 1.7 Limitations

The spatial and temporal scale of the analysis presented here imposes inevitable limitations related to
 computational resources, data availability and methodological abstraction, the most important of which
 are discussed below.

449 Ambient shoreline trends can be an important component of shoreline dynamics and depend on several factors including the various sediment sources and sinks<sup>57</sup>, along with the fate of sediments<sup>66-68</sup>. While 450 smaller-scale assessments considered in detail the above factors<sup>69</sup>, limitations in terms of modelling 451 452 capabilities and available datasets, render application of such a methodology at global scale as 453 impossible. Therefore, in the present analysis we extrapolate historically observed ambient shoreline changes AC into the future, as is common in previous studies<sup>58,70,71</sup>. This is done, however, in a 454 455 probabilistic way that allows quantifying the temporal variability and inherent uncertainty. As such, 456 future ambient shoreline dynamics follow ongoing trends within uncertainty bounds defined by the 457 spread of the observed historical changes. The 32 year time window considered may be long enough to 458 express decadal-scale variability in shoreline position, but still may not fully resolve some rare cases of 459 coastline change, like those induced by very extreme events, or sudden and drastic human

interventions. Finally, the 30 m spatial resolution of the satellite dataset may not suffice to resolvesmaller displacements in less energetic areas.

Shoreline retreat due to SLR is estimated using the Bruun rule<sup>18</sup>, which despite its known drawbacks is 462 expected to be adequate for large scale assessments<sup>9,72</sup>. The Bruun rule is based on the concept that the 463 morphology tends to reach an equilibrium state, which is supported by field observations<sup>40,73,74</sup>. 464 However, the parameterization of the equilibrium profile per se has been a subject of debate<sup>75-77</sup>, as the 465 simplified model excludes several factors controlling coastal morphology often found in nature. These 466 include, for example, sediment sinks and sources<sup>69</sup>, morphological response to SLR<sup>59</sup>, morphological 467 control from natural or artificial structures<sup>6</sup>, the presence of nearshore bars<sup>78</sup> or other morphological 468 features<sup>79,80</sup> and longshore processes<sup>66</sup>. 469

470 Still, despite the criticism<sup>75</sup>, the concept is being used extensively because any proposed improvements 471 and modifications<sup>53,81-85</sup> demand data that are often not available. In the present implementation 472 several of the shortcomings of the Bruun rule are bypassed since *R* focusses only on what the concept 473 can deliver; i.e. alongshore-averaged shoreline response to SLR and changes in wave climate. Most of 474 the factors discussed above and that are beyond the Bruun rule's capacity are expressed by the ambient 475 change AC: e.g. changes due to sediment budget imbalances, geological or anthropogenic factors.

The uncertainty related to the active profile slope is another common weakness of the Bruun rule<sup>41</sup>, which in the present analysis is addressed through the use of estimates obtained from topo-bathymetric data. The quantitative accuracy of Bruun rule estimates has also been the subject of rigorous debate for over 3 decades<sup>41,72,75,86</sup>. Here we have attempted to address this source of uncertainty by incorporating a correction factor *E* (Eq 5; see also discussion in Section 1.3), which is implemented probabilistically within the Monte Carlo framework adopted in our computations.

482 Beach profile responses to storms are simulated using the KD93 model, rather than with sophisticated 483 process-based models that incorporate elaborate numerical methods and sediment transport modules<sup>87-93</sup>. Such models can potentially provide more accurate estimations of storm erosion (if they 484 485 are well calibrated and validated), but require as input detailed topo-bathymetric and sediment grain 486 size information that is not available at global scale. The present analysis of S required the simulation of 487 circa 45 million storm events, rendering the application of models that are computationally more 488 expensive than KD93 practically impossible. In addition, KD93 has produced acceptable results in previous smaller-scale applications of similar scope<sup>94-96</sup>. 489

490 An aspect not covered in our analysis is the effect of storm clusters. It has been discussed extensively in previous studies, based either on field data<sup>40,42</sup>, or numerical models<sup>87,97-99</sup>, that storm chronology can 491 enhance the impact of individual events. These studies have also shown that storm erosion can be 492 followed by beach recovery. The latter is a complex process that is difficult to simulate<sup>73,100</sup> and requires 493 494 in situ data. Predicting the maximum erosion from storm clusters at global scale is therefore a 495 challenging task. We consider only the episodic erosion from individual storms without accounting for 496 storm groups and do not simulate post-storm recovery. Rather it is assumed that the combined, long-497 term, residual effects of erosion and recovery are included in the ambient change component AC.

498 The present analysis assumes unlimited backshore space for shoreline retreat. Some natural coastal 499 systems may have such accommodation space, while in other sites this may be strongly limited by 500 human development or physical barriers. This is a known issue which combined with SLR can have 501 societal and ecological implications discussed in the literature, especially under the term of coastal squeeze<sup>101,102</sup>. In principle, satellite imagery could provide formation on beach width<sup>103</sup> and available 502 503 space for coastal retreat at the backshore, yet such global dataset is not available. Socio-economic projections suggest that coastal development will most likely continue in the decades to come<sup>12,13</sup>, 504 505 which may further reduce the accommodating space for coastal retreat. We consider arbitrary erosion 506 threshold values to indicate potential changes that could be critical for sandy beaches. With the 507 information on backshore space and development that may be available at local/regional scales, our 508 publicly available projections could be used by scientists and practitioners to carry out more detailed 509 smaller-scale assessments.

#### 510 1.8 Additional Results

#### 511 Sea level rise retreat

512 Rising sea levels will result in shoreline retreat along the entire global coastline with the exception of a 513 few regions that experience uplift, like the Baltic Sea (Extended Data Fig. 2). The global average median 514 R by 2050 (relative to 2010) is projected to be around -28 m and -35 m under RCP4.5 and RCP8.5, 515 respectively. By the end of the century, SLR-driven erosion is projected to further grow to around -63 m 516 and -105 m, respectively. The retreat of sandy beaches due to SLR is projected to be highest (at least 130 517 m by 2100 relative to 2010 under RCP8.5) in North Australia, Central North America, North-East Brazil, 518 South and Southeast Asia, and Central Europe. Other regions for which high R values are projected 519 include West Africa, Southeastern South America, South Australia/New Zealand, East Asia and East 520 North America.

#### 521 Ambient changes

522 The present section discusses long-term ambient changes as a result of hydrodynamic, geological and 523 anthropic factors. The global averaged AC is erosive, corresponding to global average land retreat of -524 11.5 m by 2050 (very likely range between -34.7 and 11.7 m) and of -30.4 m by the end of the century 525 (very likely range between -79.1 and 18.2 m). The stronger erosion is projected for South Asia, the 526 Caribbean SIDS, and Southeastern South America with the very likely range by the end of the century 527 being from -431.8 to -238.2, from -250 to -174.2, and from -204.5 to -71.3, respectively (Extended Data 528 Fig. 3). East Asia shows a strong accretive ambient shoreline change trend (very likely range: 86.7-147.6), 529 being the result of major coastal land reclamations over the recent decades.

530 Smaller scale projections show high spatial variability with erosive and accretive trends interchanging. 531 Examples of accretion hotspots in Central America/Mexico can be found in Colombia, both on the 532 Caribbean Sea and on the Pacific Ocean, especially at the mouths of the rivers Atrato, Sinu, Magdalena, 533 Jurubida, San Juan and others. In Central North America, the long-term trends of coastal 534 erosion/accretion are dominated by the dynamics at the mouth of the Mississippi river. The area is very 535 dynamic, with large erosive spots (e.g. the Terrebonne Bay) and accretive spots (e.g. the Atchafalaya delta<sup>104</sup>). Furthermore, the area is frequently hit by tropical cyclones<sup>105</sup> that may cause abrupt extreme 536 erosion, for example hurricane Katrina, the largest natural disaster in the history of the US<sup>106</sup>, and 537 538 hurricane Rita in 2005.

In North-Eastern Brazil, the activity is dominated by the morpho-dynamics of the Tocantins delta and along the coasts of Para-Maranhao-Piaui-Ceara, a very active area characterized by both extreme coastal erosion and accretion<sup>7</sup>. The dominance of accretion is likely due to the erosivity of the soil in the interior, a rich river network that transports sediments towards the sea, and strong macro-tidal currents carrying them along the coasts<sup>107</sup>.

The most active areas in Southern Africa are the coasts of Mozambique and the Western coasts of Madagascar, areas characterized by intense tidal currents. Accretion prevails especially in Madagascar, likely due to internal erosion and subsequent transport of sediment towards the coasts, and redistribution of it by currents<sup>108</sup>.

548 Southeast Asia is characterized by both extreme erosion and accretion. Intense erosion can be observed, 549 for example, at the deltas of the rivers Sittaung<sup>109</sup> and Mekong<sup>19</sup>, or in areas of strong land subsidence, 550 like the Northern coast of Java<sup>110</sup>, or in the northern Manila Bay<sup>111</sup>. Examples of areas dominated by 551 extreme accretion are the extended delta of the Red river in North Vietnam, western New Guinea, several river deltas in the Malaysian peninsula and Sumatra, as well as in intensely built sites such as
Bangkok and Singapore. A more detailed discussion on the local/regional variations can be found in
Mentaschi et al.<sup>7</sup>.

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## 559 Author contributions

560 M.I.V, R.R. and L.F. jointly conceived the study. M.I.V. and L.M. produced the storm surge and wave 561 projections. L.M. produced the ambient shoreline change data. M.I.V. and T.A.P. produced the storm 562 erosion and sea level rise retreat projections, P.A. produced the global beach slope dataset, A.L. produced the global sandy beach presence dataset. M.I.V. analysed the data and prepared the 563 564 manuscript, with all authors discussing results and implications and commenting on the manuscript at 565 all stages. T.P. was funded by the research group RNM-328 of the Andalusian Research Plan (PAI) and 566 the Portuguese Science and Technology Foundation (FCT) through the grant UID/MAR/00350/2013 567 attributed to CIMA of the University of Algarve. The corresponding author would like to thank Drs 568 Alessio Giardino and Ap van Dongeren for providing helpful comments on the manuscript and the 569 methodology.

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### 571 Data availability

The models and datasets presented are part of the integrated risk assessment tool LISCoAsT (Large scale Integrated Sea-level and Coastal Assessment Tool) developed by the Joint Research Centre of the European Commission. The dataset is available through the LISCoAsT repository of the JRC data collection (<u>http://data.europa.eu/89h/18eb5f19-b916-454f-b2f5-88881931587e</u>) and should be cited as follows:

- 577 European Commission, Joint Research Centre (2019): Global shoreline change projections.
- 578 European Commission, Joint Research Centre (JRC) [Dataset] doi:10.2905/18EB5F19-B916-454F-B2F5-
- 579 88881931587E; PID: <u>http://data.europa.eu/89h/18eb5f19-b916-454f-b2f5-88881931587e</u>

## 580 Code availability

- 581 The code that supported the findings of this study is available from the corresponding author upon
- 582 reasonable request.

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