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African Heritage Sites threatened by coastal flooding and erosion as sea-level rise accelerates

Michalis Vousdoukas (✉ vousdoukas@gmail.com)
European Commission https://orcid.org/0000-0003-2655-6181
Joanne Clarke
University of East Anglia
Roshanka Ranasinghe
IHE Delft Institute for Water Education https://orcid.org/0000-0001-6234-2063
Lena Reimann
Vrije Universiteit Amsterdam
Nadia Khalaf
University of Exeter
Trang Duong
UNESCO-IHE https://orcid.org/0000-0003-4193-0653
Birgitt Ouweneel
University of Cape Town https://orcid.org/0000-0002-4858-0089
Salma Sabour
University of Southampton
Carley Iles
Center for International Climate Research
Christopher Trisos
University of Cape Town https://orcid.org/0000-0002-5854-1489
Luc Feyen
European Commission, Joint Research Centre (JRC) https://orcid.org/0000-0003-4225-2962
Nicholas Simpson
University of Cape Town https://orcid.org/0000-0002-9041-982X

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Abstract

Important heritage sites along the African coast are at risk from the threats associated with rising sea levels. Here, we quantify the exposure of natural and cultural heritage sites in Africa to coastal flooding and erosion in the 21st century. We develop a comprehensive database of 284 coastal African Heritage Sites (AHS), composed of 213 natural and 71 cultural heritage sites, which is then combined with coastal flooding and erosion projections to assess exposure to coastal extreme events for a moderate (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. We find that 56 AHS are presently at risk from a 100-year extreme sea-level event, with a total exposed heritage area of 2,222 km^2. Most of the currently exposed AHS are located in Northern and Western Africa. By mid-century, the number of exposed AHS is projected to increase more than 3 times to reach 191 and 198 under moderate and high emissions respectively. In the second half of the century, the number of exposed sites stabilizes, but the median exposed area increases to 6.6 to 8.5 times the present-day value, under moderate and high emissions, respectively. Mitigation from high to moderate emissions will reduce the end-century median exposed area and number of very highly exposed sites by 20% and 25% respectively.

Introduction

Natural and cultural heritage sites have important cultural, historical, social and economic value[1], yet their conservation is rarely supported by pragmatic, sustainable and stakeholder-driven solutions. As the 21st century unfolds, climate change driven hazards have the potential to seriously impact the world's heritage sites[2,3], and this is especially the case for sites located in the coastal zone, where the world is now committed to increasing sea levels for multiple millennia, regardless of mitigation. Sea levels have been rising at a faster rate over the last three decades compared to the 20th century[4,5], a process that is expected to gather pace through the 21st century[6–8]. Together with changing weather patterns[9,10] this is expected to intensify coastal flooding[11] and coastal erosion[12], exacerbating damages to coastal zone assets[13]. In contrast to other continents of the world[14–16], there are only few comprehensive assessments of the impacts of climate change along the 300,000 km long African coastline[2,3,17] spanning 38 countries. Information on the risk posed by climate change to African coastal heritage sites is very rare, with only few studies that have considered small sub-sets of sites[2,3], albeit often hampered by limited data availability.

Here, we present an assessment of exposure to coastal hazards of African Heritage sites (AHS). We first created a unique and comprehensive database of 284 coastal AHS, combining 71 Cultural World Heritage Sites and 213 Natural heritage sites that are already recognised or currently under consideration by UNESCO World Heritage Centre. The total area of the sites of interest is 512,757 km^2. The database includes the names and locations of the sites, their geospatial outline and a wide range of characteristics describing the area and elevation of each site. To assess exposure to current and future coastal flood hazard, we derived inundation maps using a hydrodynamic model forced by extreme sea levels (combination of sea level, waves, tides and storm surges). To assess coastal erosion, we post-process recent shoreline change projections of Vousdoukas et al.[12] together with site-specific geological information on the maximum possible retreat. Our analysis focuses on the coastal area exposed to a 100-year coastal flooding and erosion extreme events, and we estimate the temporal evolution of this exposed area (EA) at each site along the 21st century, under a moderate (RCP4.5) and high (RCP8.5) emissions scenario. At each site we derive EA for flooding and erosion separately and consider the union of these two as the final EA; therefore values hereinafter express the combined effect of both coastal hazards. We consider 5 classes of exposure based on the percentage of the site's total area that is exposed (EA%): no exposure, low (EA%<25), moderate (25 < EA%<50), high (50 < EA%<75) and very high (EA%>75). We further discuss exposure to the 100-year coastal extreme event in the present (taken here as 2010), as well as in 2050 and 2100. We present median values and the spread in projections considering different sources of uncertainty. We provide information for each AHS and present our findings at country, regional and continental levels (see Methods for more details on the different steps of the analysis).

Results

Out of the 284 identified AHS, we find that 56 are presently exposed to a 100-year coastal extreme event (64 under the worst-case scenario; 95th percentile). Across the continent, exposure is low, moderate, high and very high for 36, 14, 3, and 3 sites, respectively (Fig. 1). At sub-regional scale, the largest number of sites currently exposed is found in North Africa, totalling 23 out of the 109 AHS in the region (see Supplementary Information, Fig. 1 for sub-regions definition). The Western and Southern regions of the continent contain 18 and 7 exposed sites, out of 72 and 32 in total, respectively. The Eastern and Small Island regions have 4 currently exposed sites each (out of the overall 18 and 36, respectively). None of the 17 Central African sites is currently exposed. At country level, Tunisia contains the most heritage sites (34), 7 of which are exposed to a 100-year event, with 2 of them being highly exposed. Morocco and Senegal have also 7 exposed sites each (out of 26 and 13 in total, respectively), followed by Egypt with 4 being exposed out of 17.

Table 1

Coastal hazard exposure of cultural, natural, and total African Heritage Sites at continent level. Area (in km^2) and number of sites exposed to the 100-year coastal extreme event during the present century. In addition, the average percentage of the sites' exposure is shown (exposed area divided by the total site's area). The values correspond to the different emission pathways RCP4.5 and RCP8.5, by 2050 and 2100, respectively; while values in brackets, indicate the very likely range (5th -95th percentiles).

		Baseline	**RCP45-2050**	**RCP45-2100**	**RCP85-2050**	**RCP85-2100**
Natural	**Nr sites**	35 [35–40]	151 [151–152]	151 [150–152]	154 [154–160]	154 [152–160]
	Area (km^2)	1768 [1396–2121]	1781 [1403–3856]	15053 [11905–20545]	2203 [2003–4504]	18930 [13653–25545]
	average %exposure	5.1 [4.9–5.1]	5.2 [4.9-6.0]	12.4 [10.3–15.7]	6.2 [5.9–6.6]	15.0 [11.8–20.4]
Cultural	**Nr sites**	21 [21–24]	40 [40–44]	40 [40–44]	44 [44–50]	44 [40–50]
	Area (km^2)	454 [437–463]	466 [437–611]	1609 [1308–2076]	584 [559–1083]	2073 [1557–2543]
	average %exposure	2.7 [2.6–2.7]	2.9 [2.6–3.7]	7.8 [6.5–9.7]	3.5 [3.3–4.2]	9.7 [7.8–12.0]
TOTAL	**Nr sites**	56 [56–64]	191 [191–196]	191 [190–196]	198 [198–210]	198 [192–210]
	Area (km^2)	2222 [1832–2584]	2247 [1840–4467]	16662 [13213–22621]	2787 [2562–5587]	21003 [15210–28087]
	average %exposure	4.5 [4.3–4.5]	4.6 [4.3–5.4]	11.2 [9.4–14.2]	5.5 [5.2-6.0]	13.7 [10.8–18.3]

Thirty-five of the total 213 natural sites (equivalent to 16%) and 21 of the 71 cultural sites (i.e., 30%), are exposed to a 100-year coastal extreme event (Table 1). The above correspond to 1768 km^2 [1396–2121] and 454 km^2 [437–463] of exposed natural and cultural heritage area, respectively. The corresponding minimum and maximum values, indicated between square brackets express the very likely range (5th -95th percentiles). The total heritage area currently to exposed to the 100-year coastal extreme event is 2222 km^2 [1832–2584], while on average each site has 4.5% [4.3–4.5] of its area exposed.

By the year 2050, the number of AHS threatened by a 100-year coastal extreme event is projected to reach 191 [191–196] under a moderate emissions scenario (Table 1). Considering the median estimates 68, 47, 24, 23, 16 and 13 exposed sites are found in the North, Western, Southern, Small Islands, Central, and Eastern part of the continent, respectively. High emissions will increase the total number of exposed sites by mid-century to 198 [198–210], implying 7 additional sites (for the median estimate), 4 of them found in the Northern part of the continent and the remaining three are distributed among the Small Islands, Southern and Western regions. For both scenarios, the number of exposed sites remains stable in the second half of the century, but there is a sharp increase in the level of exposure. With moderate emissions, the number of very highly exposed sites increases 5 times from mid (3 [3–4]) to end-century (15 [14–20]), while under high emissions this estimate increases more than three-fold, from 6 [6–6] to 20 [17–30] (Fig. 1).

While the projected increase in the number of sites exposed to a 100-year coastal extreme event stabilize after mid-century, the projected increase in exposed heritage area accelerates as sea level rise gathers pace (Fig. 2). By 2050 and under high emissions, the median additional exposed area is limited to about 25% of the baseline value (2,222 km^2 vs 2,787 km^2), while under moderate emissions the increase is less than 2%. However, by the end of the century the median additional exposed area increases by 6.5 times its present-day value under moderate emissions, reaching a total exposed area of 16,662 km^2 [13,213 – 22,621] (Table 1). The median exposed area under high emissions is 21,003 km^2 [15,209 – 28,087], about 9.5 times the baseline value (Fig. 2). These findings underline the benefits of reducing greenhouse gas emissions, as mitigation from high to moderate emissions would result in a 26% reduction of the median exposed area, as well as 25% less very highly exposed sites, by the end of the century (Fig. 1).

Until 2050 and regardless of the scenario, less than 1% of the total cultural or natural heritage area will be exposed to the 100-year coastal extreme event, however, at least 3.3% and 2.8% of the total natural and cultural area will be exposed by the end of the century, respectively (median values; Fig. 2). These percentages are relatively low as some of the sites occupy large areas; but in average AHS will have 11.2% [9.4–14.2] and 13.7% [10.8–18.3] of their area exposed, under moderate and high emissions, respectively (Table 1). These percentages are higher for natural sites than for cultural ones; e.g. under high emissions 15% [11.8–20.4] vs 9.7% [7.8–12.0], respectively. Projections show that at least 151 natural and 40 cultural sites will be exposed to the 100-year event from 2050 onwards, regardless of the scenario (median values, Table 1). As natural sites occupy almost ten times more area than cultural ones, most of the exposed area belongs also to the former. Under moderate emissions and by the end of the century the exposed natural and cultural area will be equal to 15053 km^2 [11905–20545] and 18930 km^2 [13653–25545], respectively.

At country level and in terms of median estimates, there are several countries which are projected to have all their heritage sites exposed to the 100-year coastal extreme event by the end of the century, regardless of the scenario; e.g. Cameroon, Republic of the Congo, Djibouti, Western Sahara, Libya, Mozambique, Mauritania, and Namibia (Fig. 3; Table 2). Under high emissions and for the worst-case scenario (i.e., 95th percentile) four more countries are added to the list: Côte d'Ivoire, Capo Verde, Sudan and Tanzania. Across the continent, Morocco and Tunisia have the highest number of sites exposed by 2100 (at least 20, regardless of the scenario), at least 13 more than at the present. With respect to the heritage area exposed, Mozambique is the most exposed country (median value exceeding 5,683 km^2 under moderate mitigation; Fig. 3), followed by Senegal (> 2,291 km^2), Mauritania (> 1,764 km^2) and Kenya (> 822 km^2). Tanzania, Mozambique, Côte d'Ivoire, Benin, Togo, and South Africa are countries which by the end of the century will have at least 100 times more exposed heritage area than at present.

Table 2

Country level projections of African Heritage Sites exposure to the 100-year coastal extreme event by the end of the century, under moderate mitigation (RCP4.5) and high emissions (RCP8.5): number of sites and area exposed, as well as total number of sites and the percentage of which is exposed. Values express the median, combined with the very likely range (5th -95th percentiles) in brackets. Due to space restrictions only countries with the highest projected increase in heritage exposure are shown.

	NR Sites Exposed			**Area Exposed (km2)**			**% of country's sites exposed**			**No sites**
Country	**Baseline**	**RCP45-2100**	**RCP85-2100**	**Baseline**	**RCP45-2100**	**RCP85-2100**	**Baseline**	**RCP45-2100**	**RCP85-2100**	
BEN	1 [1–1]	3 [3–3]	3 [3–3]	1 [1–1]	402 [349–570]	503 [406–803]	20.0 [20.0–20.0]	60.0 [60.0–60.0]	60.0 [60.0–60.0]	5
CMR	0 [0–0]	3 [3–3]	3 [3–3]	0 [0–0]	37 [23–67]	59 [33–171]	0.0 [0.0–0.0]	100 [100–100]	100 [100–100]	3
COG	0 [0–0]	5 [5–5]	5 [5–5]	0 [0–0]	105 [66–195]	190 [91–439]	0.0 [0.0–0.0]	100 [100–100]	100 [100–100]	5
DJI	1 [1–1]	5 [5–5]	5 [5–5]	0 [0–0]	31 [28–39]	39 [32–55]	20.0 [20.0–20.0]	100 [100–100]	100 [100–100]	5
DZA	2 [2–2]	8 [8–9]	9 [8–10]	113 [112–113]	219 [166–237]	300 [221–345]	9.5 [9.5–9.5]	38.1 [38.1–42.9]	42.9 [38.1–47.6]	21
EGY	4 [4–4]	8 [8–8]	8 [8–8]	78 [74–78]	156 [112–192]	201 [148–221]	23.5 [23.5–23.5]	47.1 [47.1–47.1]	47.1 [47.1–47.1]	17
ESH	1 [1–1]	4 [4–4]	4 [4–4]	6 [6–6]	71 [56–127]	88 [67–165]	25.0 [25.0–25.0]	100 [100–100]	100 [100–100]	4
GAB	0 [0–0]	6 [6–6]	6 [6–6]	0 [0–0]	205 [93–350]	344 [178–611]	0.0 [0.0–0.0]	100 [100–100]	100 [100–100]	6
KEN	0 [0–0]	2 [2–2]	2 [2–3]	0 [0–0]	822 [689–1075]	1028 [756–1246]	0.0 [0.0–0.0]	40.0 [40.0–40.0]	40.0 [40.0–60.0]	5
LBY	0 [0–0]	3 [3–3]	3 [3–3]	0 [0–0]	4 [3–5]	5 [4–6]	0.0 [0.0–0.0]	100 [100–100]	100 [100–100]	3
MAR	1 [1–1]	21 [21–22]	23 [22–23]	3 [3–3]	260 [236–347]	332 [278–385]	33.3 [33.3–33.3]	80.8 [80.8–84.6]	88.5 [84.6–88.5]	26
MOZ	0 [0–0]	4 [4–4]	4 [4–4]	0 [0–0]	5683 [4235–7880]	7135 [4682–8954]	0.0 [0.0–0.0]	100 [100–100]	100 [100–100]	4
MRT	2 [2–3]	4 [4–4]	4 [4–4]	7 [7–23]	1764 [1665–2137]	2115 [1828–2555]	50.0 [50.0–75.0]	100 [100–100]	100 [100–100]	4
NAM	0 [0–0]	5 [5–5]	5 [5–5]	0 [0–0]	273 [251–331]	332 [299–377]	0.0 [0.0–0.0]	100 [100–100]	100 [100–100]	5

	NR Sites Exposed			Area Exposed (km2)			% of country's sites exposed			No sites
SEN	0 [0–0]	10 [10–11]	11 [10–11]	0 [0–0]	2291 [2138–2816]	2796 [2394–3318]	0.0 [0.0–0.0]	76.9 [76.9–84.6]	84.6 [76.9–84.6]	13
TUN	2 [2–2]	20 [20–21]	21 [20–24]	1 [1–1]	178 [135–229]	222 [165–555]	40.0 [40.0–40.0]	58.8 [58.8–61.8]	61.8 [58.8–70.6]	34
ZAF	1 [1–1]	14 [14–15]	15 [14–15]	0 [0–0]	584 [537–759]	734 [595–845]	25.0 [25.0–25.0]	70.0 [70.0–75.0]	75.0 [70.0–75.0]	20

Discussion

In our findings, more heritage area is exposed to flooding compared to erosion, but as the impact mechanism of the two hazards is different, their relative importance is site-specific. Sea level rise driven shoreline retreat would constitute a permanent damage, in contrast to temporary inundation that occurs during flooding. Cultural sites, which tend to be architectural, will be affected by both erosion and flooding, while bio-cultural and natural areas are more likely to recover from episodic flooding. Impacts will also depend on the extent to which natural coastal systems can adapt and absorb other external shocks, like for example, changes in salinity, which remains unknown[17]. Several sandy beaches of the continent are naturally protected by coral reefs and mangroves[18,19]. However, the fate of coral reefs depends on future marine heatwaves[20] and ocean acidification trends[21] - both of which are expected to increase all around the continent; while mangroves are also threatened by rising seas. For example, five species of mangroves are listed amongst biota likely to become locally extinct in Ghana, if SLR exceeds the rate of forest migration[22–24]. Such transitions could have further indirect effects and weaken natural coastal protection, further exacerbating flood risk.

Our analysis highlights that the current exposure of coastal African heritage is already concerning, as confirmed by recent events. Chatt Taboul and Parc National du Diawling in Mauritania are examples of sites already exposed to extreme flood events. Both have been negatively affected by the construction of the Diama dam in 1986 and despite efforts to ecologically restore the floodplain[25,26], future flooding and erosion due to sea-level rise may affect the ecological equilibrium of the site's ecosystem. Qaitbay Citadel of the Lighthouse of Alexandria, one of the seven wonders of the ancient world[27,28], experienced severe flooding in 2019, leading to the construction of coastal defences[29]. Colonial forts along the coastline of Ghana have been lost to extreme sea level events[30,31], while relict Guinean coastal forests have largely disappeared due to coastal erosion[32,33].

Africa is home to some of the most diverse cultural and bio-cultural heritage in the world, internationally recognised for its uniqueness and 'outstanding universal value'[34]. They have continuously served as 'living' heritage[35] and therefore are deeply interwoven with the people's identity and tradition, are essential for social wellbeing, safeguarding traditional knowledge and livelihoods, and constituting a prerequisite for sustainable development[36,37]. Our findings highlight the need for immediate protective action for AHS in view of the projected climate change-driven increase in coastal hazards[38,39].

Declarations

Correspondence

Correspondence and requests for materials should be addressed to M.I.V and N.P.S.

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Author contributions

M.I.V., N.P.S., J.C., C.H.T. and R.R. Conceptualization; M.I.V. and L.F. Methodology; M.I.V., N.P.S., J.C., R.R., S.S., C.H.T., L.R. and L.F., Validation; M.I.V. Formal analysis; M.I.V., Investigation; M.I.V., N.P.S., C.H.T., and L.F., Resources; M.I.V., N.P.S., J.C., R.R., S.S., C.H.T., B.O., N.K., C.I., T.D. and L.R. Data Curation; M.I.V Writing - Original Draft; M.I.V., N.P.S., J.C., R.R., S.S., C.H.T., T.D., L.R., and L.F., Writing - Review & Editing; M.I.V, L.R., N.P.S., N.K. Visualization; M.I.V., N.P.S., J.C. Project administration; C.H.T. Funding acquisition.

Competing interests

The authors declare no competing financial or non-financial interest.

Methods

General

We assess the exposure of African natural and cultural heritage sites to coastal hazards, with the latter expressed as the result of floods and erosion during this century. We start by generating a homogenous database of Heritage sites in Africa, compiling, validating and correcting existing information. Then, we overlay the heritage dataset with two distinct sets of hazard maps, describing the evolution of coastal flooding and sandy beach erosion during the 21st century. The study considers two greenhouse gas emission scenarios, RCP4.5 and RCP8.5, corresponding to moderate-emissions mitigation-policy and high-emissions[40], respectively.

Heritage Sites definition

We consider all African sites included in the UNESCO World Heritage List of 2020[41] and the Ramsar Sites Information Service[42,43]. Poor representation of African sites on the World Heritage List is a known issue[44,45], therefore we also consider African sites included in the UNESCO World Heritage Tentative List[46]. The latter has been proposed, recognised and endorsed as holding potential 'outstanding universal value'. Our study focusses on 71 cultural and 213 natural heritage sites found within 42 African countries with a coastline[47].

Accurate maps and coordinates of most Ramsar sites are available in the official database; in contrast to World Heritage Sites which are not always described by accurate maps and coordinates, often intentionally, to protect fragile heritage sites from looting. In addition, sites on the World Heritage Tentative List are not provided with maps or coordinates. As a result, substantial effort was expended to ensure every site included in the database was correctly delineated and geo-located. The World Database on Protected Areas (WDPA)[48] was loaded into a GIS and was used to identify missing polygons for Ramsar and Natural World Heritage Sites. Maps of sites were overlaid onto Google Earth using the image overlay function[49–51], allowing delineation of each site's boundaries. In the case of sites which were not identifiable, due to either landcover, or missing/inaccurate information, historical imagery and/or published literature were used to delineate the site accurately [52,53]. This resulted in a polygon/vector ShapeFile containing the master table of all sites (see Supplemental Material). The dataset also includes additional metadata, such as the area, and the mean, minimum and maximum elevation of each site, including the officially designated heritage site number. In the present analysis of coastal exposure, sites found at elevations above 50 m are excluded, as they are considered not vulnerable to rising seas. The filtering was done using elevation data from the 3 arc seconds GLO-90 DEM available by the Copernicus Services[54], and the threshold elevation is sufficiently high to ensure that no site is erroneously excluded due to vertical bias of the DEM (in the worst case few meters).

Sea level rise, tides, waves and storm surge

Hindcasts of waves and storm surges (1980–2015) are obtained through dynamic simulations forced by ERA-INTERIM atmospheric conditions. Storm surges are simulated using the DFLOW FM model[55], and the waves using the third-generation spectral wave model WW3[56,57]. Both models have been extensively validated with detailed information provided in the references above as well as in Vousdoukas et al. [55]. Tropical cyclones, not fully represented by global reanalyses[58], have been simulated by the DFLOW FM model forced by the IBTrACS best-track archive[59]. Cyclone effects on the waves are considered using the peak maxima of Hs measured by altimeter data provided by 6 different satellites[60]: ERS-2, ENVISAT, Jason 1 and 2, Cryosat 2 and SARAL-AltiKa.

Present-day tidal elevations (η_{tide}) are obtained from the FES2014 model[61]. Following the approach of Vousdoukas et al.[55], the high tide water level is considered, taking into account the range due to the spring-neap tide cycle. Probabilistic SLR projections from Jevreyeva et al.[62] and DFLOW FM[63] are then used to assess changes in global tidal elevations due to changing sea levels[55]. Simulations of wave and storm surge until the end of the century are forced by outputs from 6 CMIP5 climate models[56,57].

Coastal inundation

Inundation maps along the entire the coast of Africa are obtained following the approach presented by Vousdoukas et al.[64], using the Lisflood-ACC (LFP) model[65,66]. Simulations are based on the GLO-90 DEM[54]. Land hydraulic roughness is derived from land-use maps[67]. The inundation modelling takes place over coastal segments distributed along the coast, with spacing of 25 km with each other and extending up to 200 km landwards. The simulations are forced by extreme sea levels (ESLs) defined as the combination of mean sea level (MSL), astronomical tide (η_{tide}) and meteorological tide (η_{CE}; i.e. the combination of storm surge and the wave setup[68]). All components are combined in Monte Carlo simulations which allow quantifying the full range of uncertainty and produce probability density functions of ESLs. In this analysis, we focus on the median value of the 100-year event, obtained from non-stationary extreme value analysis[69].

To assess heritage sites exposed to coastal flooding we overlay the heritage site polygons with the inundation maps for each RCP (i.e., RCP4.5, RCP8.5) and time step studied (i.e. 2010, 2030, 2050, 2070, 2090, 2100). Given that some sites are partially under water even under normal (i.e., non-ESL) conditions, we exclude areas inundated by the present-day high tide water level. Subsequently, we calculate the area flooded (in km²) and the share of the site flooded (in %) in each scenario and time step, based on Reimann et al.[2].

Coastal erosion

Projections of shoreline change driven from ambient factors, RSLR and episodic erosion during extreme storms are available from Vousdoukas et al.[12]. The projections are probabilistic, providing full probability density functions every 10 years until 2100. Shoreline change is the combined result of three components: (1) ambient shoreline dynamics driven by long-term hydrodynamic, geological and anthropic factors[70,71]; (2) shoreline retreat due to RSLR, estimated using a modified version of the Bruun rule[12]; (3) episodic erosion during extreme storms (as with the floods, we focus on the 100-year event), estimated after detecting extreme events from global wave projections datasets and simulating beach profile response at each global location (the analysis includes millions of simulations and is described in detail in Vousdoukas et al.[12].

The existing projections of Vousdoukas et al.[12] express potential shoreline change, assuming infinite amount of sediment supply and accommodating space for coastal retreat at the backshore. As a result, additional effort was put to identify where and to what extent shoreline retreat in the vicinity of Heritage Sites would be interrupted by the presence of unerodable surfaces and other specific geological conditions. Starting from the dataset on the spatial distribution of sandy beaches along the African coastline from Luijendijk et al.[71], we consider additional information to identify which sites are actually exposed to coastal erosion. The Global Lithological Map (GLiM)[72] is the most accurate dataset describing the properties of surface rocks worldwide and is used to identify rocky coastlines, while additional natural and man-made obstacles to shoreline retreat were identified through inspecting the time-history of satellite images from Google Earth. At beaches where obstructions to shoreline retreat were identified, the retreat projected by Vousdoukas et al.[12] was limited to the erodible area seaward of the obstruction. After the above processing we identify 6 cultural and 55 natural sites which are considered as potentially exposed to coastal erosion.

Combined coastal hazard

The above steps result in estimates of the exposed area to coastal flooding and erosion for all the combinations of heritage sites, emission scenarios, years and percentiles (1, 5, 16 50, 84 and 99). For each case, we consider the total affected area as the maximum of the area exposed from each of the two hazards. We also estimate the percentage of the total area exposed (EA%), defining 5 classes of exposure: no exposure, small (EA%<25), moderate (25 < EA%<50), high (50 < EA%<75) and very high (EA%>75).

Apart from discussing the results at site level, we also group at country, as well as regional levels. We also focus on the median, 5th and 95th percentiles (very likely range), under the two emissions scenarios considered here.

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. Once the paper will be accepted the Afra Heritage Sites dataset, as well as the flood risk assessment data will be available through the LISCoAsT repository of the JRC data collection (http://data.jrc.ec.europa.eu/collection/LISCOAST).

Code availability

The code that supported the findings of this study is available from the corresponding author.

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Figures

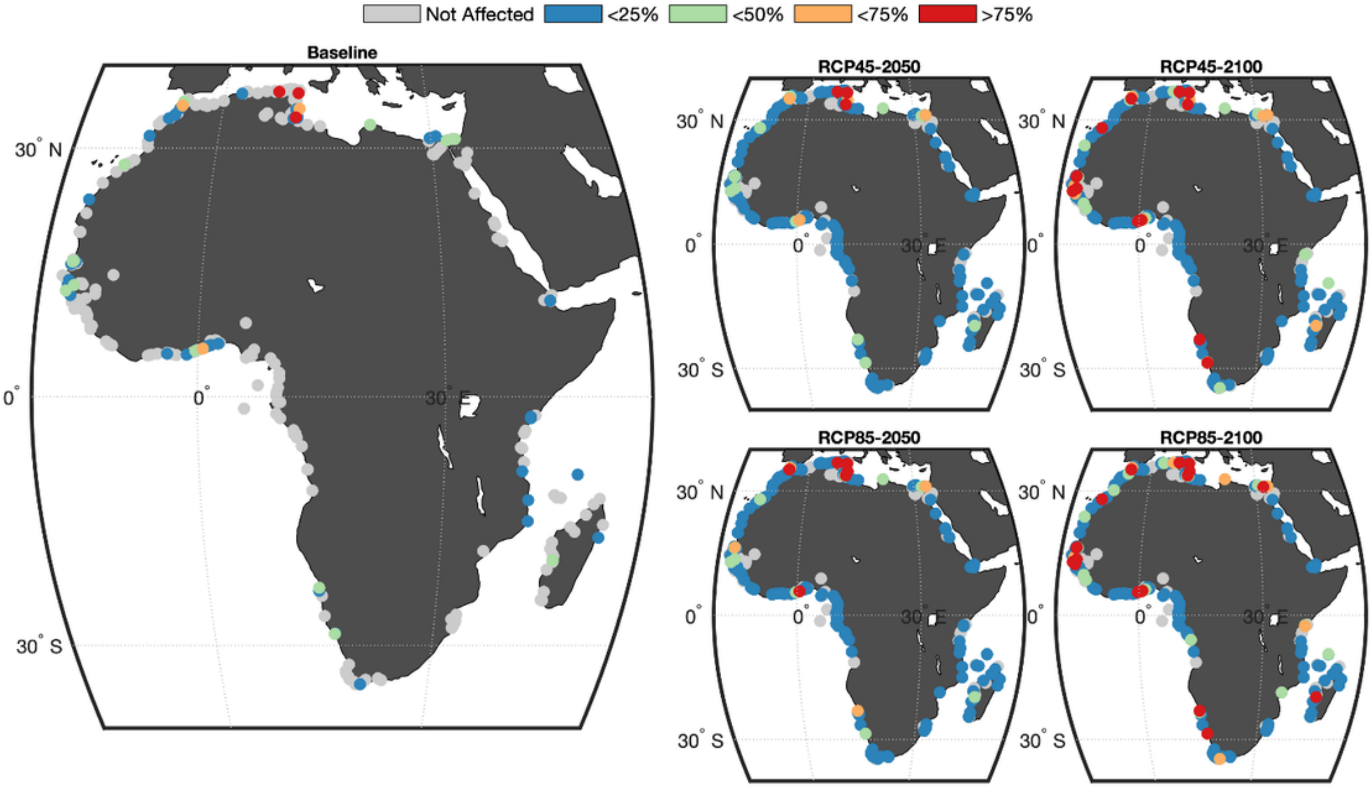

Figure 1

Maps of African Heritage Sites affected by the 100-year coastal extreme event, during the baseline period (left panel) and under RCP4.5 and RCP8.5, during the years 2050 and 2100. The dots indicate the location of the sites, colours blue, green, orange, and red implies that less than 25% or at least 25%, 50%, 75% of the total site's area is exposed to coastal hazards.

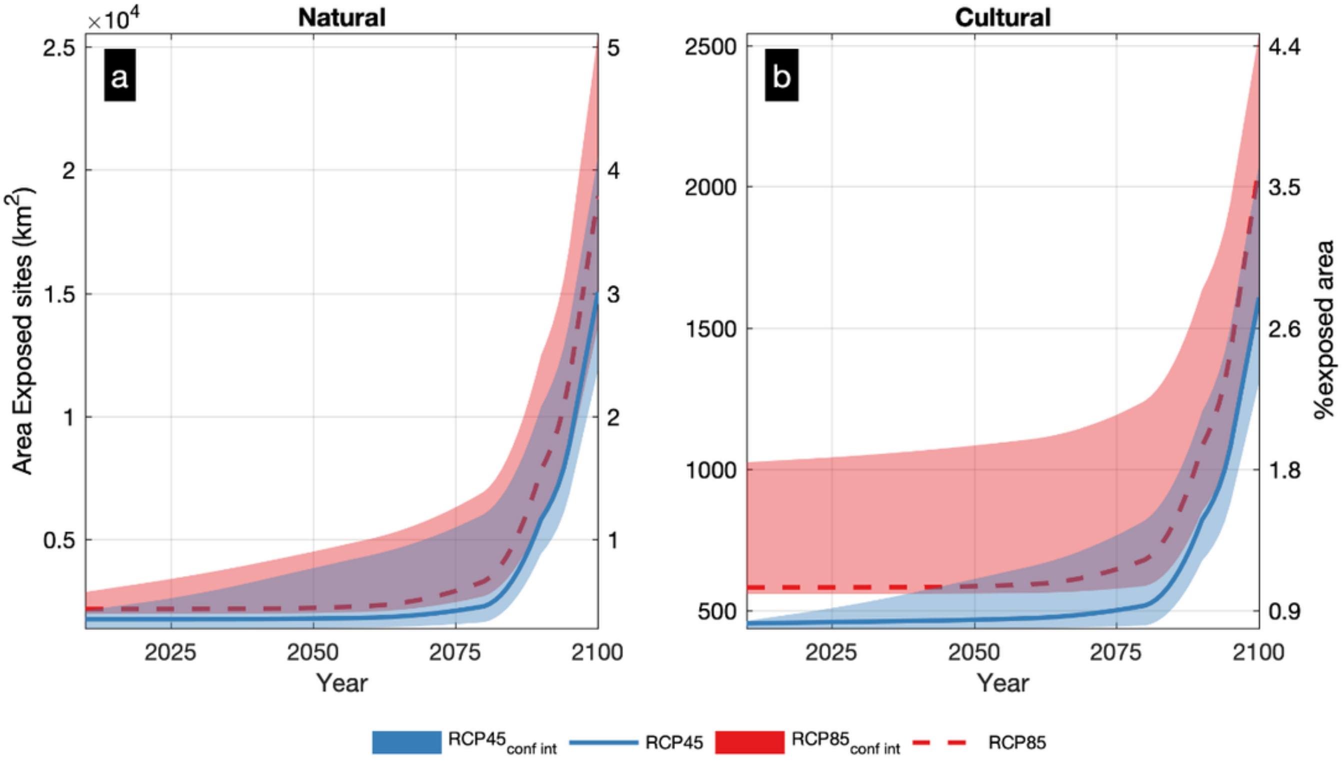

Figure 2

Time evolution of the area of natural (a) and cultural (b) African Heritage Sites affected by the 100-year coastal extreme event, during the 21st century. Median values are shown for RCP4.5 (blue solid line) and RCP8.5 (red dashed line), while respectively shaded areas indicate the very likely range (5th-95th percentiles). The left vertical axis expresses affected area in km2 and the right one the percentage of the total heritage area.

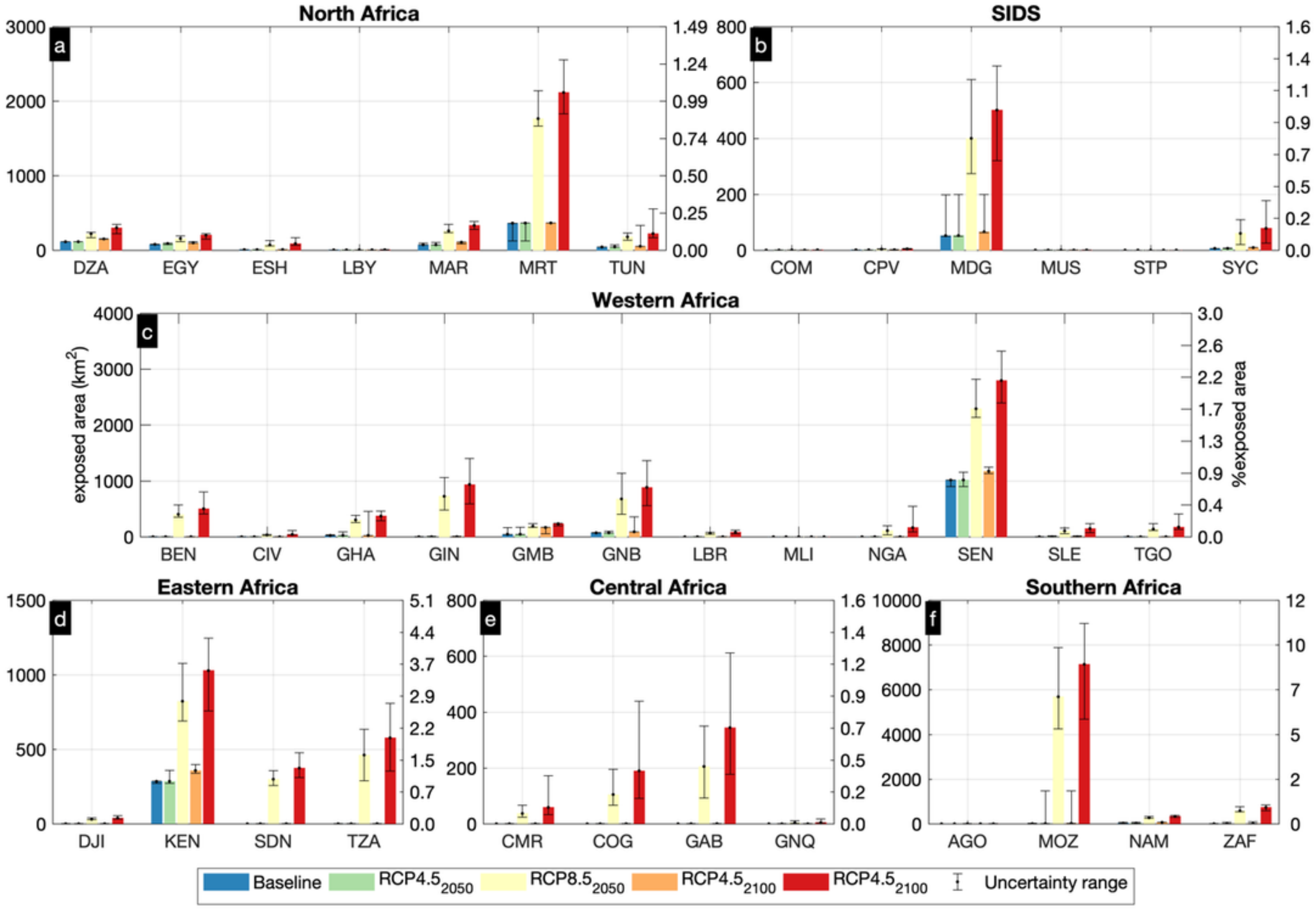

Figure 3

Country estimates of the area of African Heritage Sites affected by the 100-year coastal extreme event during the 21st century. Projections are grouped in regional subplots with blue indicating the baseline and green, yellow, orange and red corresponding to projections for the different emission pathways RCP4.5 (green, orange) and RCP8.5 (yellow, red), by 2050 and 2100, respectively. Thin bars indicate the very likely range (5th-95th percentiles) and the left and right vertical axis expresses affected area in km2 and the corresponding percentage of the total sub-regional area, respectively.

Supplementary Files

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