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Climate change and coastal archaeology in the Middle East and North Africa: assessing past impacts and future threats

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Abstract

Climate change is a threat to coastal archaeology, with impacts resulting from storm flooding (Extreme Sea-Level: ESL), long-term sea-level rise (SLR) and coastal erosion. There remain large global gaps in baseline evidence, for instance in the Middle East and North Africa (MENA). We present here a methodological demonstration and initial results from an assessment of climate change threats to the coastal heritage of the MENA region. This is based on the newly-developed Maritime Endangered Archaeology (MarEA) inventory which provides an up-to-date digital geospatial database of maritime archaeological sites from MENA incorporating as standard a disturbance and threat assessment. These data inform two analyses of past disturbance and future threat: 1) based directly on the integral threat/disturbance assessment and 2) geospatial extraction of information from existing models of coastal change (Global Surface Water, LISCoAsT, CoastalDEM90). These analyses suggest a small core of coastal sites (< 5%) is definitely affected by coastal erosion. However, many more (up to 34% of the documented coastal record), may also have been affected by flooding, erosion or storm action in the recent past. More than 40–50% of coastal sites could be impacted by climate change-related processes in some form over the 21st Century. SLR and ESL could impact on 14–25% of sites by 2050 and 18–34% by 2100. Over 30% of coastal sites could be impacted by erosion by 2050 and over 40% by 2100. All climate change-related threats will also increase over the 21st Century with a post-2050 acceleration, if carbon emissions remain high, and place considerable pressure on the unique coastal archaeological record. Whilst documentation is ongoing and there remain uncertainties in this modelling, these data and approaches provide a viable means to redress the frequent absence of baseline data on climate change impacts and coastal cultural heritage in the MENA region.

1. Introduction

Anthropogenic climate change is acknowledged as one of the greatest threats humankind is facing today, with the potential to adversely impact natural systems and human societies over the 21st Century and beyond (IPCC 2014; IPCC 2019a; IPCC 2019b). Cultural heritage is not immune to these impacts (Sabbioni et al. 2006; Fatorić and Seekamp 2017; McGovern 2018; Hambrecht and Rockman 2017). Maritime cultural heritage, which incorporates coastal, intertidal and underwater heritage, is regarded as especially at risk because coastlines and intertidal zones are subject to the considerable impacts of erosion and flooding, driven by long-term sea-level rise (SLR) or by episodic events such as storms, hurricanes and tropical cyclones (Erlandson 2008; Erlandson 2012; Fitzpatrick, Rick, and Erlandson 2015; Harkin et al. 2020; Murphy, Thackray, and Wilson 2009; Dawson et al. 2020). Secondary impacts on archaeological and heritage sites are created by the human response to climate change. Hard infrastructure such as seawalls and breakwaters may prevent erosion or flooding and protect sites inland, but coastal sites may be damaged by these measures, if they are located at the point of construction. Moreover, hard defences can also shift erosion elsewhere along a coastline, and thus simply move the location of greatest threat (Cooper and Pile 2014; Cooper, O'Connor, and McIvor 2020; Cooper and Jackson 2019). Alternatives, such as soft- or ecological engineering (e.g., the creation/restoration of natural habitats: (Morris et al. 2018) or managed realignment (Esteves 2014) are desirable from a coastal management standpoint since they provide a more natural and sustainable means of shoreline stabilization. However, they are often dynamic since shorelines are allowed to migrate or flood (Morris et al. 2018). Thus, while there are examples of archaeological sites which have been protected in this manner (Harkin et al. 2020), others remain at risk (Daly 2011; Krawiec 2017).

Awareness of climate change impact on coastal cultural heritage is increasingly established, along with a rapidly growing body of research (Fatorić and Seekamp 2017). Published approaches include desk-based assessment, flood modelling, remote sensing, shoreline change assessment, archaeological field survey, UAV survey, community-based projects and adaptation planning (Robinson et al. 2010;

Westley et al. 2011; Daire et al. 2012; Westley and McNeary 2014; Dawson 2015; Reeder-Myers 2015; Andreou et al. 2017; Anderson et al. 2017; Graham, Hambly, and Dawson 2017; O'Rourke 2017; Ezcurra and Rivera-Collazo 2018; Ives, McBride, and Waller 2018; Reimann et al. 2018; Westley 2019; Cook, Johnston, and Selby 2019; Elliott and Williams 2019; Reeder-Myers and McCoy 2019; Rivera-Collazo 2020; Hil 2020; Dawson et al. 2020). Clear common themes are emerging from this diverse body of work. These include awareness that not all sites can be saved, the importance of rapid documentation to record cultural material before it is lost, and the need to assist historic environment / cultural resource managers in prioritizing attention, resources and interventions through improved data on climate change and sites at risk.

Nevertheless, and despite the global impact of climate change, the recent literature reveals an uneven distribution of research. Numerous projects are ongoing or completed in North America and Europe, often with the active engagement of national heritage agencies (Robinson et al. 2010; Westley et al. 2011; Daire et al. 2012; Westley and McNeary 2014; Dawson 2015; Reeder-Myers 2015; Anderson et al. 2017; Graham, Hambly, and Dawson 2017; O'Rourke 2017; Heilen, Altschul, and Lüth 2018; Ives, McBride, and Waller 2018; Nash and Wholey 2018; Westley 2019; Cook, Johnston, and Selby 2019; Elliott and Williams 2019; Reeder-Myers and McCoy 2019; Murphy, Thackray, and Wilson 2009; Hambrecht and Rockman 2017; Heathcote, Fluck, and Wiggins 2017; Harkin et al. 2020). Despite the rich maritime cultural heritage outside Europe and North America, attempts made elsewhere are few in number (Fatorić and Seekamp 2017; Brooks et al. 2020).

An example of this is the Middle East and North Africa (MENA). Although it has a longstanding and well-published tradition of maritime and coastal archaeology - particularly in the Mediterranean (e.g., Blue 2019) - research has often focused on specific sites or topics of study. For example, shipwrecks, ancient harbour development or trade networks (e.g., Marriner, Morhange, and Carayon 2008; Marriner and Morhange 2008; Robinson and Wilson 2011; Galili, Oron, and Cvikel 2018). Moreover, discussions of sea level and climate have focused principally on past change (e.g., Benjamin et al. 2017; Inglis et al. 2019; Galili et al. 2020; Lambeck et al. 2011) rather than the impacts of present and future change on the endangered archaeological record. There are a handful of exceptions, which include one national-level (Israel: Galili and Rosen, 2010) and one comprehensive regional risk assessment (Reimann et al. 2018), with the latter geographically and thematically restricted to Mediterranean World Heritage Sites. Outside these, the tendency is to discuss climate change impacts in terms of individual sites (see section 3.6) or generalized potential impacts (Brooks et al. 2020; Trakadas 2020). The upshot is a gap in knowledge which lies between site-specific snapshots and generalized overviews of potential impact. The missing information is precisely the type of baseline data on maritime cultural heritage (e.g., site locations, present condition) and impacts (e.g., severity, spatio-temporal variability) which is needed to start producing comprehensive threat assessments. This means that archaeologists and/or heritage agencies cannot often address even basic questions. For instance, which sites will be affected by climate change impacts? Where is the threat greatest along a given coastline? By when and how will particular sites be affected? This in turn hinders the development of prioritization and management strategies which can minimize the loss of irreplaceable cultural heritage.

Addressing this at national and regional levels requires comprehensive and up-to-date digital inventories of archaeological sites. Within these, additional requirements are accurate site locations to enable geospatial modelling or assessment of threats (Reimann et al. 2018; Reeder-Myers 2015; Hil 2020; Westley et al. 2011) and use of standardized terminology to enable direct comparison of variables such as threat or site types (Rayne et al. 2017). Outside MENA, threat assessments have been able to adapt national heritage inventories for these purposes (e.g., Anderson et al. 2017; Westley and McNeary 2014). However, within MENA the availability and quality of such inventories, and the skills and technology needed to produce them are highly variable (Rayne, Sheldrick, and Nikolaus 2017). This has been the impetus for a recent series of threat assessment programmes which include the generation of new digital databases, such as Endangered Archaeology of the Middle East and North Africa (EAMENA: Rayne et al. 2017) and the ASOR Cultural Heritage Initiative (Danti, Branting, and Penacho 2017).

In 2019, this approach was extended into the MENA coastal/nearshore zone via the Maritime Endangered Archaeology Project (MarEA). MarEA is supported by the Arcadia Fund, a charitable fund of Lisbet Rausing and Peter Baldwin, and works in partnership with EAMENA (Rayne et al. 2017; Andreou et al. 2020). Its overarching aim is to comprehensively document and assess threats to the maritime cultural heritage of the MENA region. Documentation and assessment is based on remote sensing analysis supplemented where possible by other data, such as literature, field observations and/or geophysical survey. Results are fed into the open access EAMENA database (https://database.eamena.org/). The end result is an up-to-date digital inventory and threat assessment of maritime archaeological sites which fulfils the core requirements of geospatial accuracy and standardized terminology and thereby enables quantification and comparison of threats across the MENA region.

This paper presents initial results from a component of the overall MarEA analysis, specifically the mapping and quantification of climate change impacts on coastal archaeological sites. For the purpose of this analysis, 'coastal' is defined as the present shoreline and adjacent Low Elevation Coastal Zone (LECZ: land areas <10m in elevation and in hydrological connection to the coast (IPCC 2019b) (see section 4 for rationale and S1 for technical details). These results are based on the initial 1.5 years of documentation and not all MENA countries are currently represented (see section 4). However, given the urgency of the climate crisis, we cannot wait until the 'perfect' dataset is available. It makes sense to start identifying where threats are now and developing strategies to deal with them rather than delaying in the hope of more and better data. Over time, as more data becomes available, initial results can be refined and more countries and coastlines included. Moreover, the analysis presented here demonstrates different approaches to regional-scale threat assessment which can fill the current knowledge gap, specifically manual documentation of threats and disturbances versus geospatial integration of the digital inventory with external models of climate change impact.

In the following sections, we firstly provide background to the physical environment, maritime cultural heritage and likely coastal climate change impacts in the MENA region; secondly, we provide initial results of climate change impact and threat identification; finally, we discuss the implications of analysis to date and potential future work.

2. Background: Physical geography, climate change and coastal archaeology in the Middle East and North Africa

2.1 Physical geography

The MENA region has 55,000 km of coastline bordering the Atlantic Ocean, the Mediterranean Sea, the Indian Ocean and the Red Sea, Gulf of Aden and Arabian/Persian Gulf. Coastal and nearshore zones are topographically diverse. Areas of steep mountains and narrow continental shelves contrast with broad coastal plains and extensive shelves (Figure 1). Roughly 175,000 km^2 of the MENA region are LECZ and thus are at risk from coastal flooding (Figure 1). Extensive LECZ is located at the northern Arabian/Persian Gulf, Nile Delta and Gulf of Sirte. Elsewhere, it comprises a coastal fringe of varying width, generally expanding around estuaries and embayments.

MENA wave climates vary between the oceanic swell-dominated coast of northwest Africa, the protected semi-enclosed basins of the Mediterranean and Red Seas, and the tropical cyclone-influenced Arabian Sea. Tidal range varies from mesotidal (2–4 m) on the Atlantic coast and in the Arabian Sea and Arabian/Persian Gulf to microtidal (< 2 m) in the Mediterranean and Red Seas (Rosendahl Appelquist 2013). Consequently, extreme sea-levels (ESL) created by the combined effect of storm waves, tides and surges differ across the region. The highest ESL (2–3 m) are restricted to parts of the Arabian/Persian Gulf and Atlantic coast. Remaining areas are typified by ESL of < 1 m, with localized excursions up to 1.5 m (Muis et al. 2016). Local to regionally-varying wave and tidal regimes and differing geology and topography, all contribute to a diversity of coastal geomorphologies. This includes, for example, extensive beaches, archipelagos, coastal dunes, mangroves, estuaries, deltas, rock cliffs and platforms, intertidal flats and sabkhas (Bird 2010).

2.2 Coastal archaeology

The MENA region has been occupied by humans and their hominin ancestors since the Lower and Middle Palaeolithic (Raynal et al. 2001; Scerri and Spinapolice 2019; Scerri et al. 2018; Petraglia, Breeze, and Groucutt 2019; Daujeard et al. 2020) including sites within, or close to, the former coastal zone (Walter et al. 2000; Ramos et al. 2008; Sinclair et al. 2019; Besançon et al. 1994; Beyin and Shea 2007). Throughout the Quaternary, the MENA coastal zone experienced major fluctuations in relative sea-level (RSL) in line with glacial-interglacial cycles and with local- to regional-scale variation caused by tectonics and the isostatic response to distant ice sheets and changing water loads (Lambeck and Chappell 2001; Grant et al. 2014; Lambeck et al. 2011; Benjamin et al. 2017; Vacchi et al. 2018). The region has attracted significant scholarly attention due to material evidence for several early key processes including the development of crop agriculture, animal husbandry, and sedentary life as part of the 'Neolithic revolution' (Cauvin 2000; Simmons 2007; Watkins 2010), early processes of social hierarchy, urbanization (Liverani and Tabatabai 2014), and state formation (Bang and Scheidel 2013) developing into some of the world's earliest empires (Düring and Stek 2018; Van de Mieroop 2004), and the foundation of powerful maritime societies (Horden and Purcell 2000; Broodbank 2013). Given the comparative lack of permanent waterways for inland navigation (aside from exceptions such as the Nile), the sea has played a major role in regional trade and transport. Ancient shipping routes traversed the Mediterranean, Red Sea, Arabian Sea and Indian Ocean (Boivin, Blench, and Fuller 2010; Seland 2011; Leidwanger 2020) and the coastline is dotted with coastal settlements, trading stations, constructed ports and natural harbours, generally dating from the mid- to late-Holocene onwards. Sea-level and coastal geomorphological changes continued into these recent periods, and are complicated by local and regional variations in neotectonics and sediment supply (Morhange et al. 2006; Anzidei et al. 2011; Inglis et al. 2019; Vacchi et al. 2018; Zerboni et al. 2020). Thus, for all periods, pre-existing 'maritime' sites and landscapes can be found along the coast, buried under the present coastal plain, submerged offshore or uplifted above present sea-level and now inland.

2.3 Climate Change Impacts

A key driver of coastal climate change impacts is sea-level rise (SLR), itself the end result of ocean warming and ice melting. Global projections indicate SLR of 0.29–1.1 m by 2100. This takes the upper and lower bounds of the likely range for the IPCC's Representative Concentration Pathways (RCP) 2.6 and 8.5, respectively best- and worst-case projections of 21st Century atmospheric greenhouse gas concentrations. SLR rates are currently 3.1–4.1 mm/yr and projected to accelerate over the 21st Century (IPCC 2019b). Modelled uncertainties also increase in time. Thus, 'pessimistic' models with greater SLR (up to 1.5–2 m by 2100) driven by accelerated Antarctic melting cannot be excluded (Kopp et al. 2017; IPCC 2019b; Pattyn and Morlighem 2020). SLR projections for MENA follow these trends, albeit slightly reduced, due to region-specific tectonic, oceanographic and isostatic effects (Figure 2). The expectation is that MENA will experience ~0.2 mm of SLR by 2050 under all RCPs but with acceleration thereafter if GHG emissions remain at elevated levels (RCPs 4.5 and 8.5). The result is SLR of ~1.5 m by 2100 under a pessimistic scenario, reducing to 0.8 m under a conventional high emissions RCP. Models also indicate minor regional variability with SLR in the east of the region 0.1 m higher than in the west (Kopp et al., 2017, 2014; Waha et al., 2017; World Bank, 2014).

SLR can impact coastlines in several ways. Firstly, it will result in permanent inundation of present-day dryland. This impact will be most extensive in areas that are currently subsiding (e.g., Nile Delta) or which have extensive LECZ (e.g., northern Arabian/Persian Gulf, Gulfs of Gabes and Sirte) (El Raey 2010; Dasgupta et al. 2011). Secondly, it will amplify the threat of Extreme Sea Level (ESL) events (i.e., the combined effect of tides, storm surges and mean sea-level) such that even relatively small SLR can lead to a significantly increased flood intensity and frequency. For instance, the return period for extreme events can be reduced such that a 1-in-100-year flood becomes an annual event (Kopp et al. 2014; Kopp et al. 2019; Vousdoukas et al. 2018). Frequency amplification is enhanced where historic sea-level variability due to tides and surges is small compared to projected future SLR (IPCC 2019b). These conditions characterise much of the MENA coastline given its often microtidal and semi-enclosed nature. Consequently, modelling suggests strong amplification, particularly in the Red Sea and Indian Ocean, such that the return period of 1-in-100-year ESL becomes an annual event by 2050, under both medium (RCP4.5) and high (RCP8.5) emissions pathways. Projected amplification is less severe for the Mediterranean, but shows a reduction in return period to < 20 years (Vousdoukas et al. 2018). Regarding ESL height, increases are projected for the entire MENA region. By 2050 under both RCPs 4.5 and 8.5, increases of up to 0.4–0.5 m relative to present are apparent everywhere. By 2100, ESL values rise by up to 0.6 m under RCP4.5, and even further under RCP8.5: generally by up to 1 m for the Arabian Peninsula and varying between 0.6—1 m for North Africa (Figure 3). Thirdly, SLR has the potential to alter the balance between erosion and accretion on a given coastline. Recent modelling suggests that SLR is the key factor responsible for increasing erosion rates of sandy shorelines over the 21st Century rather than episodic storms (Vousdoukas et al. 2020). This model projects widespread coastal retreat of tens of metres by 2050 across MENA, and often exceeding 100 m by 2100 under RCPs 4.5 and 8.5 (Figure 4). This should be taken with the caveat that these models are necessarily simplified to enable a global-scale approach, and that the precise coastal response at any given location can be more complex than predicted (Cooper et al. 2020).

In addition, human attempts to adapt to changing climates can also have adverse impacts. The most obvious are engineering solutions that protect the coast, but at the cost of altering natural hydrodynamics and sediment supply. These can inhibit the natural response of coastal systems and potentially shift erosion elsewhere (Cooper and Pile 2014; Cooper and Jackson 2019; Cooper, O'Connor, and McIvor 2020). Additional indirect impacts could result from societal responses to climate change away from the coast. For example, declining rural livelihoods caused by climate change impacts on water and agriculture could increase rural-to-urban migration (World Bank 2014; Waha et al. 2017; Cattaneo et al. 2019). This pressure, coupled with the fact that the MENA population is projected to double by 2050 (World Bank 2014), could result in accelerated urban expansion. Since many of MENA's major urban centres are on the coast, the impacts here will be considerable. Human action unrelated to climate change may exacerbate the impact of the processes above. For example, groundwater extraction can result in subsidence which in turn locally enhances SLR. Within MENA, this effect has been noted for the Nile Delta (Egypt) (El Raey 2010; Stanley and Clemente 2017; Rateb and Abotalib 2020). Other problematic activities include reduction or modification of sediment supply caused by coastal sand mining or damming and land-use practice further upstream in watersheds (Defeo et al. 2009; Luijendijk et al. 2018; Vousdoukas et al. 2020; Besset, Anthony, and Bouchette 2019) Such activities result in accelerated coastal retreat and have been observed at multiple locations particularly along the North African coast, including the Nile Delta (Moussaid et al. 2015; Trakadas 2020; Poulos and Collins 2002; Hzami et al. 2021).

2.4 Impacts on coastal heritage

There is already evidence within MENA of the types of adverse impacts on coastal heritage which could be heightened by climate change. For instance, extensive erosion has been observed in Eastern Libya. Here, waves and storms cut into low cliffs of unconsolidated coastal sediment, exposing and damaging archaeological material buried within the cliff or undercutting structures built on top of it. The impact is particularly severe due to the numerous Classical to Roman-period ports, harbours and settlements dotted along this stretch of coast. Well-known examples where destructive erosion has been observed include Tocra and Apollonia (Flemming 1965; Bennett 2018; Bennett and Barker 2011; Bennett et al. 2004; Pizzinato and Beltrame 2012). Reports from MarEA's local partners indicate that erosion is ongoing (Figure 5) and that its destructive effects can be seen also on a series of no-less important but less well-studied sites (Hesein 2014). Other locations where erosion or coastal retreat has been noted include: Syria (Arab al-Milk: Westley et al. 2018); Libya (Sabratha: Bennett and Barker 2011; El-Shahat, Minas, and Khomiara 2014); Lebanon (Byblos: Deroin, Kheir, and Abdallah 2017), Tell Burak: Semaan 2016); Israel (Galili and Rosen 2010), Oman (Ra's al-Hamra: Tosi 1975; Marcucci et al. 2014); Morocco (Essaouira, Sidi Abdeselam de Behar: Trakadas 2020) and Iran (Siraf: Khakzad et al. 2015; Pourkerman et al. 2018). Episodic storm-driven coastal flooding is less well documented than erosion. Nonetheless, examples do exist from Syria (Arwad Island: Hassan, Xie, and Rahmoun 2018), Oman and Yemen (Charabi 2010; Newton and Zarins 2019). More common is evidence of long-term submergence of archaeological sites. In particular, the Mediterranean coasts of the Levant and North Africa contains numerous examples of port/harbour facilities, quarries, fish ponds and occupation sites now located below present sea-level (Benjamin et al. 2017; Anzidei et al. 2011; Semaan 2016). Whilst submergence is historically the result of long-term glacio-eustatic SLR and/or tectonic subsidence or sediment compaction, rates of SLR over the 21st Century suggest similar impacts will become much more widespread, even for locations which are not currently subsiding.

3. Materials and methods

Results presented here are extracted from the MarEA inventory, which is incorporated into the open access EAMENA database (https://database.eamena.org/). At the time of writing, this comprises data from the initial 1.5 years of documentation from an overall 5-year project duration. Results are thus initial and represent only a portion of the potential record to be documented. The focus of documentation in this initial phase of the project has been countries with high levels of threat (e.g., Yemen, Libya) or areas not/poorly covered by our partner EAMENA, so as to spatially expand overall coverage (e.g., Sudan, Oman).

Documentation is comprehensive: all sites are documented regardless of whether they have been subject to disturbance or are at risk. Thus documented sites range in date from the Palaeolithic to the early 20th Century and cover a variety of site types, including settlements, burials, ports/harbours, shipwrecks, buildings and enclosures. Each documented site is subject to a disturbance and threat assessment which can be used to identify disturbed or threatened sites, or extract information on particular causes of threat/disturbance. This assessment is based on recent Very High Resolution (VHR: < 1 m) satellite imagery (sourced primarily from Google Earth) supplemented by other data sources where available, including literature, historic imagery (aerial, satellite, ground-level), historic maps, geophysical data and field survey. Disturbance describes impacts which are visible on satellite imagery or reported in the literature. Threat is estimated subjectively based on the disturbance trends observed by the data analyst. These are recorded in terms of both generalized categories and detailed causes of threat and disturbance.

In all cases, consistency is maintained by use of controlled vocabularies and certainty qualifiers (e.g., definite, high, medium, low are used to account for interpretative uncertainties (see also Rayne et al. (2017) and Supplementary Information for further details on documentation and disturbance/threat assessment).

This approach does not identify climate change as a specific threat or disturbance cause for two reasons. Firstly, the immediate disturbances/threats are from natural processes or anthropogenic actions which may be affected or exacerbated by climate change. It is these immediate disturbances/threats which are recorded. Secondly, it can be difficult to disentangle which disturbances/threats are a direct outcome of climate change or have a portion attributable to climate change. Nevertheless, several types of disturbances/threats are included in the controlled vocabulary which are the most likely to be exacerbated by climate change – principally flooding and erosion.

Results are presented from two analytical approaches. The first directly analyses the threat and disturbance assessments manually created for each record. The second integrates the MarEA inventory with existing models of climate and environmental change. This uses the spatial information recorded for each documented site to extract relevant information from the integrated climate/environmental change model. Three models were integrated with these data, one focusing on past disturbance and two on future threat.

1. Past disturbance was based on the Global Surface Water dataset (GSW: Pekel et al. 2016)). This used satellite imagery to quantify the spatial extent of water gained or lost from the Earth's surface over the past 30 years and includes refinements to address coastal change (Mentaschi et al. 2018).
2. Modelled future flooding was based on the CoastalDEM90 elevation model (Kulp and Strauss 2019) combined with SLR and ESL projections generated by the Large Scale Integrated Sea-level and Coastal Assessment Tool (LISCoAsT) (Vousdoukas et al. 2018). Results were extracted for 2050 and 2100 timesteps under medium (RCP4.5) and high emissions pathways (RCP8.5)

3. Modelled future erosion was based on shoreline change projections generated by LISCoAsT (Vousdoukas et al. 2020). Results were extracted for 2050 and 2100 timesteps under medium (RCP4.5) and high emissions pathways (RCP8.5)

All above approaches focused on a subset of 1386 coastal archaeological sites filtered out from the initial dataset of 5609 sites. As mentioned earlier, for this exercise 'coastal' is defined as the present shoreline and adjacent LECZ. This broad definition has been chosen to include those sites which are, in theory, on the present front line of coastal climate change impacts, as well as sites located inland which could be affected if processes such as erosion and flooding extend landwards in the future. In contrast, the full dataset includes sites located offshore and fully underwater, and spread across the coastal hinterland up to 25 km inland. Further details on filtering and analysis methods can be found in the Supplementary Information.

4. Results: Disturbance

4.1 MarEA documentation

At face value, disturbances potentially relating to climate change, such as coastal erosion or flooding, rank low. Using all certainty qualifiers, Coastal Erosion/Retreat has only been identified for 5% of all documented sites, while the combined total of Inundation and Flooding accounts for only 1% of all sites (Figure 6, Table 1). However, these low numbers could be driven by uncertainty in the definitive identification of these causes (discussed further in section 7). Alternative causes, which encompass both coastal flooding and erosion are 'Water Action' or 'Wind and/or Water Action'. These are generic terms which denote that there has been an impact from water and/or wind, but that the exact process is unclear. Thus, the predominant identified disturbance cause is Wind and/or Water Action. Using all certainty values, this cause has disturbed 34% of the documented subset. This reduces to 23% if only high certainties are used, suggesting that there is some uncertainty in its attribution. Following this, there is a slight divergence between identified disturbance causes, though the general pattern is a mix of natural and anthropogenic. The next most common causes are: Construction (16% all certainties /

13% high certainties), Road/Track (13% / 9%); Water Action (8% / 7%), Vegetation/Crops/Trees (7% / 2%).

Disturbance patterns can also be mapped spatially. These are constrained by the areas documented to date and this bias will be corrected as the project proceeds. Nonetheless, the analysis here indicates existing hotspots of disturbance. Figure 7 does this for causes which are potentially linked to climate change, either via direct (Coastal Erosion/Retreat, combined Wind and/or Water Action and Water Action) or indirect impacts (Construction). Disturbances from construction are spread across the region, with particularly dense clusters in Eastern Libya, Sudan and Syria. An extensive but less dense cluster is also evident along the coast of the southern Arabian/Persian Gulf. Definitively identified disturbances from coastal erosion are much less widespread. Again, Syria and Eastern Libya are hotspots and smaller but dense clusters are also mapped in Sudan and on the southwest and northeast shores of Oman. Nonetheless, if water (and/or wind) action is used as a potential proxy for climate-change related processes, then the extent of disturbance becomes far more widespread. Almost every region surveyed to date has sites impacted by this cause. Some areas correspond to those where coastal erosion has already been identified (e.g., Syria, Eastern Libya, Oman), but new clusters also appear on the Sinai Peninsula, Yemen and along the shores of the Gulf of Aden and Arabian/Persian Gulf

4.2 Integration with GSW

MarEA data were spatially overlaid on the GSW dataset and re-classified on the basis of whether sites intersected one of the following coastal change categories (Mentaschi et al. 2018).

1. Land Loss: Land converted to sea/intertidal zone (coastal retreat)
2. Land Gain: Sea/intertidal zone converted to land (coastal advance)

This analysis indicate that higher proportion of sites were affected by land loss (12%) compared to land gain (2%) (Table 2). The highest density clusters for Land Loss are Eastern Libya, northern Syria, central Sudan, southwest Yemen and the southern shore of the Arabian/Persian Gulf (Figure 8). Scattered lower clusters also occur in Lebanon and along the Oman coast. Land Gain however, is spatially much more limited. The main hotspots occur in Eastern Libya, Syria and the central UAE, with isolated clusters in the Sinai Peninsula, Sudan, Yemen and Oman.

5. Results: Threat

5.1 MarEA documentation

As with disturbances, clearly identifiable causes which might be exacerbated by future climate change rank low (Figure 6, Table 1). Coastal Erosion/Retreat and the combined total of Inundation and Flooding have only been identified for 7% and 2% of sites respectively, using all certainties. On the other hand, the generic, but still potentially climate change-related cause of Water and/or Wind Action is the predominant threat. Using all certainties, 39% of the sites in the coastal subset are at risk. This reduces to 28% if only high certainties are used. The next greatest identified threat causes are a mix of natural and anthropogenic: Occupation/Continued Use (15% all certainties / 8% high certainties); Construction (13% / 5%), Vegetation/Crops/Trees (10% / 8%); and Water Action (9% / 8%).

Spatial mapping using the coastal subset and high certainties, and for causes which are potentially directly or indirectly linked to climate change, demonstrates regional patterns. Threat from construction has concentrations in Eastern Libya, the Sinai Peninsula and along the coast of the UAE. Isolated hotspots are present in Syria, Sudan and Yemen (Figure 7). In terms of erosion, only Eastern Libya and isolated occurrences in the southeast Arabian/Persian Gulf and Oman coast have clear indications of this future threat. However, as noted in section 8, this may relate to the difficulty of detecting erosion. Instead, if water action is considered as a potential indicator of climate-change related processes, then the extent of threat becomes widespread. Almost every region surveyed to date has sites potentially at risk, and given the coastal focus, water action in this case mainly comprises processes such as wave, tidal and storm action which can result in coastal flooding and erosion. For this cause, Eastern Libya, southwest Yemen, Syria, southwest Oman and the Arabian Persian Gulf are hotspots of threat.

5.2 Future threat: flooding (LISCoAsT SLR and CoastalDEM90)

This analysis suggests that several hundred sites across the region will be affected by coastal flooding from either long-term SLR or ESL (Table 2, Figure 9). This respectively equates to 13–18% or 24–34% of the documented coastal subset depending on the RCP and timestep. At the most immediate risk (i.e., RCP4.5 2050) are clusters of sites in Sudan, southwest Yemen and the UAE. Smaller clusters are also evident in Lebanon, Syria and Eastern Libya. Comparison between SLR and ESL also highlights that the number of sites potentially at risk almost doubles with ESL, and in addition to increasing cluster density, more sites at risk appear in Oman and in Eastern Libya. The pattern for 2050 under both RCPs 4.5 and 8.5 is also broadly similar, with only a handful more sites at risk under the latter. By 2100, the location of clusters of sites at risk remains broadly stable, but there are increases in the absolute numbers of sites at risk. This increase compared to 2050 is relatively minor for long-term SLR under RCP 4.5 (~2%), but more marked for ESL (~4%). For RCP8.5, the pattern is the same, but the increase in risk is proportionally greater compared to RCP4.5: ~4% for SLR and ~9% for ESL. This highlights that risk will increase with SLR and particularly if storm surges increase in frequency and magnitude (Vousdoukas et al. 2018). Stronger increases in risk will also occur if carbon emissions remain high (RCP8.5). However, the raw numbers also mask the vulnerability of certain site types; for example, most historic harbours (excepting those silted up and buried inland) are directly at the water's edge and thus at high risk of flooding and storm impacts.

5.3 Future threat: erosion (LISCoAsT Shoreline Change)

These data suggest that under each RCP and timestep, several hundred sites across the region will be affected by coastal retreat (Table 2, Figure 10). By 2050 under both RCP4.5 and 8.5, the densest clusters of impacted sites occur in Sudan, southwest Yemen, the south-eastern Arabian/Persian Gulf and Eastern Libya. Lower density clusters are also present in Egypt (northwest coast and Sinai Peninsula), Syria and Oman. By 2100 the pattern is largely similar under both RCP4.5 and RCP8.5 with a slightly expanded range of sites centred on the core areas mentioned above. RCP8.5 increases the number of sites at risk, not so much in terms of their spread outside the core areas, but more in the form of increased site density within these areas. While this clustering is partly a product of the spatial coverage of documentation to date, it does start to flag up locations of threat or lack thereof. For example, there is a gap along the coast of the UAE, where LISCoAsT projections indicate that coastal advance rather than retreat will be prevalent during the 21st Century (Figure 10).

In term of proportion of sites at risk, these projections are somewhat alarming: up to 40% of coastal sites are project to be at risk by 2050 and increasing to 43% by 2100 (RCP8.5). The caveat is that doubt has been cast on the underlying shoreline change model. It is which is regarded by some coastal scientists as overly alarmist and an oversimplification of complex coastal responses to SLR (Cooper et al. 2020). If so, these values should be regarded as the upper end of risk projections. Nevertheless, these data also highlight clear increases with time and carbon emissions. For example, a difference of 1.6% between the two 2050 RCPs versus 3.5% for the 2100 RCPs. This is in line with accelerated SLR post-2050 under a high emissions pathway.

6. From regional to local: site-level impacts

From the above we can identify areas and sites which are presently at risk and or which will be at risk in the future. In addition, documentation and model integration can also be used to explore the reasons behind local to regional patterns of vulnerability and assess the validity of conclusions derived from model integration. Examples are presented here for illustration.

6.1 Eastern Libya

A hotspot of impact is located along the coast of Eastern Libya. Here, disturbance from erosion is evident from both GSW and MarEA documentation. Together, these indicate that 8–14% of coastal sites have been affected (Table 3). These patterns are corroborated by the literature and ground observations. For example, at the Hellenistic- and Roman-period coastal settlement of Tocra, recent satellite images highlight ongoing coastal erosion: the central part of the site has eroded by ~11m between 2002 and 2019. This matches observations by Bennett et al. (2004) who identified this area as highly vulnerable because the cliff here is composed of easily-eroded wadi deposits. A series of archaeological structures were also identified/recorded (Figure 11) eroding out of the cliff. Satellite imagery resolution is insufficient to distinguish the precise condition of these features. However, the amount of cliff retreat coupled with images showing that the adjacent beach is periodically stripped to bedrock suggest a low likelihood of their survival. This is further substantiated by reports from local partners who identify that erosion is ongoing (Figure 5B).

This threat of erosion is also identified for other sites along this coast (e.g., Apollonia: Figure 5A) and supported by LISCoAsT projections which suggest that 25–26% of coastal sites will experience erosion impacts by 2050 and increasing to 32–33% by 2100 (Table 3). For SLR, based on the CoastalDEM90 and LISCoAsT modelling, long-term SLR is less of a threat than erosion: a maximum of ~20% of coastal sites will be affected by 2100 under RCP8.5. This is because the many documented sites are located > 2 m above present sea-level. However, flood impacts from episodic storms and accompanying ESL represent similar level of threat to erosion; 27–28% of coastal sites will be affected by 2050, and 30–33% by 2100 (Table 3). Overall, along this stretch of coastline the high degree of vulnerability is a product of both a concentration of archaeological sites, a natural propensity for coastal erosion and the enhanced frequency and magnitude of ESL over the 21st Century.

6.2 Suakin (Sudan)

In other cases, the pattern of vulnerability is also partly a product of the intensity and availability of previous research that was incorporated into the documentation process. This is exemplified by the central Sudanese coast where a dense cluster is present in almost all disturbance and threat maps (Figures. 7 to 10). This corresponds to Suakin; an Islamic port and settlement occupied since the 10th Century AD. In the MarEA inventory, Suakin and its immediate environs include 99 documented records, which range from Medieval Islamic structures to British Colonial-era fortifications (Figure 12). This rich documentation has been enabled by published surveys, descriptions and historic maps (Breen, Rhodes, and Forsythe 2015; Rhodes 2011; Breen et al. 2011). Thus, Suakin stands out as the rest of the Sudanese coastline is not well-studied. It also provides an example of where MarEA assessments can differ from model-generated projections.

Here, the disturbance assessments and the conclusions based on GSW are broadly similar: a moderate proportion of sites has been impacted by processes such as water action, coastal erosion and land loss (Table 4). The same is true of the flooding threat as modelled using LISCoAsT projections and CoastalDEM90: 8–10% of coastal sites will be impacted by ESL by 2050, increasing to 15–21% by 2100 and with fewer affected by long-term SLR (maximum of 9%). This is not significantly different to the 10% of coastal sites documented to be threatened by Water Action. However, future erosion threat projections are quite different. The LISCoAsT projections suggest that 82% of coastal sites will be at risk by 2050 and 95% by 2100. These figures are considerably higher than the combined threat of Coastal Erosion and Water Action from MarEA documentation (maximum of 28% of coastal sites using all certainties). Several reasons can be advanced for this. The MarEA threat assessments in this case are based on comparison of satellite imagery and available literature, neither of which show clear past instances of extensive erosion or flooding. This could indicate that the LISCoAsT erosion projections are overestimates, particularly considering the criticisms of Cooper et al. (2020). Also, Suakin itself lies within a narrow protected and fetch-limited channel. This topographic feature is not well-resolved by the LISCoAsT data, while its sheltered setting may result in erosion being less severe than on the exposed open coast (Figure 12). Extensive anthropogenic modification including armouring of the shoreline and extensive land reclamation at the mouth of the channel (neither incorporated into LISCoAsT) might be expected to have additional protective effects.

6.3 Qana (Yemen)

Even where identified clusters of risk are small or relatively low density, individual sites may also be at considerable risk. An example of this is the ancient port town of Qana (or Qani/Kané, present Bir ‘Ali) in Yemen, broadly dated between the 1st Century BCE and the early 7th Century CE. Architectural remains of the ancient town have been well preserved on the ground surface, and are mostly situated on a relatively flat and low-lying isthmus (Figure 13). Several dozen buildings of varying size have been identified, including sanctuaries, warehouses, workshops, and houses (Mouton, Sanlaville, and Suire 2006; Salles and Sedov 2010). The ancient harbour areas of the site on the north and south side of the isthmus have now been infilled by sediments, which potentially have covered old harbour installations such as moorings and jetties, artefacts, and shipwreck remains (Davidde, Petriaggi, and Williams 2004). The site has been disturbed in modern times in various ways including bulldozing activity, archaeological excavation, and continuous use as a landing place for small-scale fishing. Future threats to the site include flooding as a result of projected sea-level rise related to climate change. CoastalDEM90 analysis suggest that more than half of the site (ca. 30 ha) is situated less than 4 m above present sea-level (asl). Within this area are numerous archaeological features situated < 2 m asl. Given projected ESL of 1.6–1.7 m by 2050, and 2–2.4 m by 2100, this makes them vulnerable to flooding or increased wave action. This could damage and disturb the architectural remains and artefacts on the site's surface or within the site's ancient harbour areas.

7. Discussion

Current thinking in climate change adaptation suggests that there are commonalities in current needs including a requirement for secure baseline information from a combination of scientific data and local knowledge (IPCC 2019b: 99). For archaeology, documentation projects such as MarEA and EAMENA fulfil the first part of this by providing evidence-based assessments of site locations, types, condition, disturbance and threat. As demonstrated here, the resulting information can be analysed in a standalone fashion, or integrated with other models in order to derive information on regional patterns of threat and disturbance. Consequently, there is a now a feasible means of comparison across wide areas (including within and between counties), which is a first step towards prioritized action.

Initial results from standalone MarEA documentation find clear, albeit relatively limited, evidence of disturbance causes which could be exacerbated by climate change, such as coastal erosion. Examples of this concentrate particularly in Eastern Libya, but also with smaller hotspots in Syria, Sudan and

Oman. In quantitative terms, overall numbers are low: ~3–5% of documented sites (variation dependent on certainty levels). Using the same criteria, < 2% of sites are documented as affected by flooding/inundation. However, integration of MarEA data with the GSW dataset identifies up to 12% of sites potentially affected by long-term coastal retreat over the past 30 years.

This difference may be due to limitations in the data used for documentation. For instance, positive identification of erosion can be hindered by the quality and resolution of freely-available satellite imagery. Distinct eroding cliff lines (e.g., Tocra: Figure 11) are visible, but more subtle, low-lying or less distinct erosional features are harder to distinguish. Differences in shoreline position caused by waves and tides at time of image acquisition, coupled with positional shifts in successive images caused by georeferencing errors, also make it harder to determine if the coast has definitely retreated or advanced. This is further exacerbated where the temporal resolution of available imagery is limited and prevents shoreline comparison at regular intervals. For flooding, the episodic nature of storm flooding, coupled limited temporal resolution of available imagery, reduces the probability of having an image of a given storm event. This is further reduced by the likelihood of cloud cover during storms. Thus, without high-quality supporting data, it can be difficult to definitively identify causes of coastal disturbance, particularly if they proceed at a slow pace, or episodically. Consequently, many sites are instead documented with the more generic threat/disturbance causes 'Water Action' or 'Wind and/or Water Action'. If attribution is limited to high certainties only, then the combination of GSW integration and MarEA documentation suggest that at least 12–34% of coastal sites have experienced past disturbance from natural forces which could be exacerbated by climate change. Importantly, given the projected direction of travel of climate change, sites now at risk will remain so in the foreseeable future.

Regarding future threat, the MarEA documentation presents a similar pattern. Relatively low numbers are projected to be at risk based on coastal erosion (2–7%) and flooding/inundation (1–2%) causes. These values are perhaps unsurprising since threat assessments are based on available imagery and/or documentation. Thus, if disturbance by flooding is not observed, for the reasons outlined above, then it is unlikely to be identified as a threat. As with disturbance though, the potential effects of flooding or erosion are also identifiable in the greater numbers classified as at risk from Water Action or Wind/Water Action causes (~35–48%). The spatial distribution of threat is similar to disturbance in that erosion is largely restricted to Eastern Libya and the Arabian/Persian Gulf, but water action extends across all surveyed areas (Figure 7).

Again, these values can be compared with those from external models: flooding based on LISCoAsT projected SLR and ESL combined with elevation values from CoastalDEM90, and erosion based on the LISCoAsT shoreline change model. Flood projections suggest that ~13% of all documented coastal sites will be impacted by long-term SLR by 2050, a figure which increases to ~18% by 2100 under RCP8.5. ESL is modelled to modelled to increase in magnitude and frequency in line with SLR (Vousdoukas et al. 2018). Since ESL values exceed SLR, the proportion of sites at risk from episodic flooding or wave action increases from at least ~24% in 2050 (RCP4.5) to ~34% in 2100 (RCP8.5). Whilst there is still likely to be some degree of regional variability in vulnerability given local variation in wave and tidal exposure, results to date suggest that all surveyed areas will experience this effect. The threat from erosion/coastal retreat is similar to that of ESL. Based on the LISCoAsT model, at least 31% of sites will be affected by 2050 (RCP4.5) increasing to ~43% by 2100. The caveat is that this model is probably the most tentative, particularly given shortcomings identified by Cooper et al. (2020) and also discrepancies noted in the Suakin example. Until improved modelling is available, these estimates should therefore be regarded as worst case and/or low probability scenarios.

Taking the above together it could be argued that up to ~39–58% of coastal sites (i.e., MarEA documentation: combined total of Flooding/Inundation, Water Action, Wind/Water Action and Coastal Erosion, range reflects certainty classes) could be affected by some combination of erosion and/or flooding. Of these sites, by ~13–14% will likely be affected by long-term SLR, and ~25–34% impacted by ESL by 2050. Given the well-established nature of SLR projections, coupled with use of the most recent global coastal elevation model (CoastalDEM90) there is reasonable confidence in these figures. It is possible that up to 33% of coastal sites will be affected by erosion or shoreline retreat by 2050 and almost 43% by 2100, but there is significant uncertainty in this estimate.

In addition to the above quantification, three additional general observations can be made. Firstly, given the projected pattern of climate change, these problems will increase over time. Up till 2050 impacts from erosion and flooding are fairly similar regardless of RCP, but post-2050, acceleration is likely under RCP8.5. This highlights that the future severity of impacts depends in large part on how wider society responds to the climate crisis. Secondly, given that the modern coastal zone contains the bulk of sites associated with maritime activities from the Later Holocene onwards, this places a unique subset of sites, such as harbours, fish traps and coastal settlements, at risk. Thirdly, though not the focus of this paper, the documentation exercise also hinted that anthropogenic actions comprise significant disturbances/threats, particularly in terms of infrastructure and urban expansion (see Table 1). Thus, as coastlines experience more pressure from demographic movements and population increase, the expectation is that this threat will increase. Large-scale coastal defence projects, coupled with intensive infrastructural change, are evident throughout the region. This means that while flooding and erosion spring to mind as the most destructive impacts of climate change on coastal archaeological sites, we should not ignore the likelihood that indirect human actions such as coastal infrastructure, urbanization, sand mining and upstream damming and land-use change could also have a significant adverse impact. As such, this is an area where further research is required.

The analysis and observations presented here clearly shown that we can go some way to filling the gap in baseline knowledge of coastal heritage and climate change impacts in MENA. Equally importantly, they highlight where there are still uncertainties which require additional research to overcome. This is a consequence of data limitations (in terms of availability and resolution), the absence of up-to-date on-the-ground information and also uncertainties in existing models. Often, we can identify that sites are located on or close to the current shoreline, and thus will likely be affected by SLR, ESL and erosion. However, the exact pattern of response is presently unclear. Modelling attempts, as done here using LISCoAsT, are possible, but can be doubt as to how well some of these approaches downscale to a site or local level particularly when considering complex geomorphological responses (Cooper et al. 2020). In some respects, this is to be expected. Other studies have shown differences between broad-scale models or desk-based assessment and more detailed research, often incorporating field survey (Westley 2019; Westley and McNeary 2014; Hil 2020; Rivera-Collazo 2020) and illustrate the necessity of working at multiple scales to tackle different aspects of the climate change problem. The need for greater nuance in threat assessment extends also to other considerations such as site significance or value. As presented here, risk quantification considers each site as equal regardless of whether it is, for example, an isolated single findspot or extensive settlement. Thus, it is possible that regional to national patterns of vulnerability will change if this is included as a variable; for instance, with low density clusters of high value sites flagged up as having higher vulnerability than areas with more, but lower value sites even though the climate change threat is the same. Therefore, areas of focus for future improvement could include: 1) refined threat assessment for particular sites or site types, chosen either because of risk levels or archaeological significance; 2) Conducting on-the-ground field survey for both condition assessment and to assess coastal change which can be fed back into documentation and threat assessment; 3) Developing and testing different approaches to threat assessment, such as vulnerability indices (e.g., Reeder-Myers 2015; Reimann et al. 2018) which can integrate a range of threats including both natural and human, and potentially incorporate additional variables such as significance.

8. Conclusion

Scientific evidence indicates that climate change over the 21st Century and beyond is inevitable. Some archaeological sites, particularly those on the coast will be adversely impacted, in some cases damaged and in the worst cases completely destroyed. Baseline information is essential for archaeologists and heritage managers to start dealing with this problem, initially in terms of raising awareness and then providing practical information that can inform prioritization of attention and resources. Progress in addressing these impacts has been made, generally in North America and

Europe, but other countries lack essential baseline information such as up-to-date digital inventories onto which threat assessments can be built. In this paper, we have demonstrated how this gap can filled for the MENA region via a newly-developed digital geospatial inventory which incorporates damage and threat assessment. This forms part of a wider programme threat assessment in partnership with, the EAMENA programme. We show here that the MarEA inventory can be analysed in different ways, either through direct use of integral disturbance/threat assessments or by geospatially extracting relevant data from existing models of environmental/climate change. Initial results highlight that a small core of coastal sites (< 5%) is definitely affected by coastal erosion and will continue to be so in the future. However, potentially up to 34% of the documented coastal record may also have been affected by some combination of flooding, erosion or storm action. Estimates suggest increased numbers will be at risk from climate change-related processes in the future; possibly exceeding 50% of documented coastal sites by the end of the century. SLR and ESL could impact up to 14–25% of sites by 2050 and 18–34% by 2100. Erosion projections estimate that over 30% of coastal sites could be impacted by 2050 and more than 40% by 2100. We stress though that these estimates are tentative. There is uncertainty stemming either from the underlying models or also variable quality of data available for the documentation process. Even so, these estimates indicate that there is currently a problem, and one which will increase over the 21st Century with projected global climate changes and with a post-2050 acceleration if atmospheric GHG concentrations are not reduced. It also shows that coastal sites, which often form a unique component of the archaeological record, will be particularly strongly impacted via a combination of SLR, storms, erosion and possibly human action directly or indirectly resulting from societal responses to climate change. More work remains to be done, both within and outside MENA, to safeguard the unique coastal component of the archaeological record. However, approaches which aim to develop baseline evidence provide a clear basis for initiating threat assessment regionally and nationally, ensuring a secure foundation on which future strategies of planning, prioritization and adaptation can be built.

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Tables

	% Coastal Sites affected (n=1386)			
Cause	**Disturbance (All cert.)**	**Disturbance (High cert.)**	**Threat (All cert.)**	**Threat (High cert.)**
Coastal Advance/Accretion	2.60%	2.45%	1.52%	0.79%
Coastal Erosion/Retreat	5.27%	3.39%	7.22%	2.38%
Construction	15.58%	13.20%	12.91%	4.91%
Flooding	0.22%	0.07%	0.65%	0.07%
Inundation	1.23%	1.23%	1.52%	1.01%
Occupation/Continued Use	6.28%	4.26%	15.37%	8.44%
Ploughing	1.95%	0.87%	2.81%	2.45%
Road/Track	13.26%	9.04%	7.93%	5.04%
Vegetation/Crops/Trees	7.43%	2.24%	9.52%	8.01%
Water Action	8.15%	6.64%	9.45%	7.58%
Water and/or Wind Action	34.27%	22.66%	39.39%	27.78%
Wind Action	3.17%	0.43%	2.24%	1.80%

Table 1. Percentage breakdown of documented MarEA sites for selected disturbance and threat causes. Selected causes include natural processes potentially linked to climate change, and the most common anthropogenic impacts. Comparison includes all certainty classes and a filtered version using only high certainty classes.

Analysis Type	**Model**	**Category/Timestep and RCP**	**Coastal Subset (n = 1386)**	
			No. of sites	**% of dataset**
Disturbance	*GSW*	*Land Loss*	170	12.3%
		Land Gain	29	2.1%
Threat	*ESL: LISCoAsT + CoastalDEM*	*RCP4.5 2050*	337	24.3%
		RCP4.5 2100	397	28.6%
		RCP8.5 2050	351	25.3%
		RCP8.5 2100	476	34.3%
Threat	*SLR: LISCoAsT + CoastalDEM*	*RCP4.5 2050*	182	13.1%
		RCP4.5 2100	211	15.2%
		RCP8.5 2050	192	13.9%
		RCP8.5 2100	247	17.8%
Threat	*Coastal erosion/retreat: LISCoAsT shoreline change*	*RCP4.5 2050*	433	31.2%
		RCP4.5 2100	550	39.7%
		RCP8.5 2050	454	32.8%
		RCP8.5 2100	599	43.2%

Table 2. Summary breakdown of sites potentially impacted by coastal changes based on the integration of MarEA data with models of coastal change. Sites are shown in terms of the raw count of documented sites as well as percentages.

Analysis Type	Model/Approach	Category/Timestep and RCP	Coastal Subset (n = 180)	
			No. of sites	% of dataset
Disturbance	*MarEA documentation*	*Construction (All Cert)*	42	23.3%
		Construction (High Cert)	30	16.7%
		Coast Erosion (All Cert)	26	14.4%
		Coast Erosion (High Cert)	10	5.6%
		Water Action (All Cert)	70	38.9%
		Water Action (High Cert)	7	3.9%
Disturbance	*GSW*	*Land Loss*	15	8.3%
		Land Gain	7	3.9%
Threat	*MarEA documentation*	*Construction (All Cert)*	42	23.3%
		Construction (High Cert)	34	18.9%
		Coast Erosion (All Cert)	26	14.4%
		Coast Erosion (High Cert)	24	13.3%
		Water Action (All Cert)	64	35.6%
		Water Action (High Cert)	59	32.8%
Threat	*ESL: LISCoAsT + CoastalDEM*	*RCP4.5 2050*	48	26.7%
		RCP4.5 2100	54	30.0%
		RCP8.5 2050	51	28.3%
		RCP8.5 2100	59	32.8%
Threat	*SLR: LISCoAsT + CoastalDEM*	*RCP4.5 2050*	22	12.2%
		RCP4.5 2100	28	15.6%
		RCP8.5 2050	26	14.4%
		RCP8.5 2100	37	20.6%
Threat	*Coastal erosion/retreat: LISCoAsT shoreline change*	*RCP4.5 2050*	45	25.0%
		RCP4.5 2100	57	31.7%
		RCP8.5 2050	47	26.1%
		RCP8.5 2100	59	32.8%

Table 3. Breakdown of threat and disturbance results from MarEA documentation and extant model integration for Eastern Libya.

Analysis Type	**Model/Approach**	**Category/Timestep and RCP**	**Coastal Subset (n = 99)**	
			No. of sites	**% of dataset**
Disturbance	*MarEA documentation*	*Construction (All Cert)*	19	19.2%
		Construction (High Cert)	16	16.2%
		Coast Erosion (All Cert)	3	3.0%
		Coast Erosion (High Cert)	2	2.0%
		Water Action (All Cert)	9	9.1%
		Water Action (High Cert)	7	7.1%
Disturbance	*GSW*	*Land Loss*	10	10.1%
		Land Gain	0	0.0%
Threat	*MarEA documentation*	*Construction (All Cert)*	12	12.1%
		Construction (High Cert)	2	2.0%
		Coast Erosion (All Cert)	8	8.1%
		Coast Erosion (High Cert)	0	0.0%
		Water Action (All Cert)	10	10.1%
		Water Action (High Cert)	10	10.1%
Threat	*ESL: LISCoAsT + CoastalDEM*	*RCP4.5 2050*	8	8.1%
		RCP4.5 2100	15	15.2%
		RCP8.5 2050	10	10.1%
		RCP8.5 2100	21	21.2%
Threat	*SLR: LISCoAsT + CoastalDEM*	*RCP4.5 2050*	8	8.1%
		RCP4.5 2100	8	8.1%
		RCP8.5 2050	8	8.1%
		RCP8.5 2100	9	9.1%
Threat	*Coastal erosion/retreat: LISCoAsT shoreline change*	*RCP4.5 2050*	80	80.8%
		RCP4.5 2100	93	93.9%
		RCP8.5 2050	81	81.8%
		RCP8.5 2100	94	94.9%

Table 4. Breakdown of threat and disturbance results from MarEA documentation and extant model integration for Suakin.

Figures

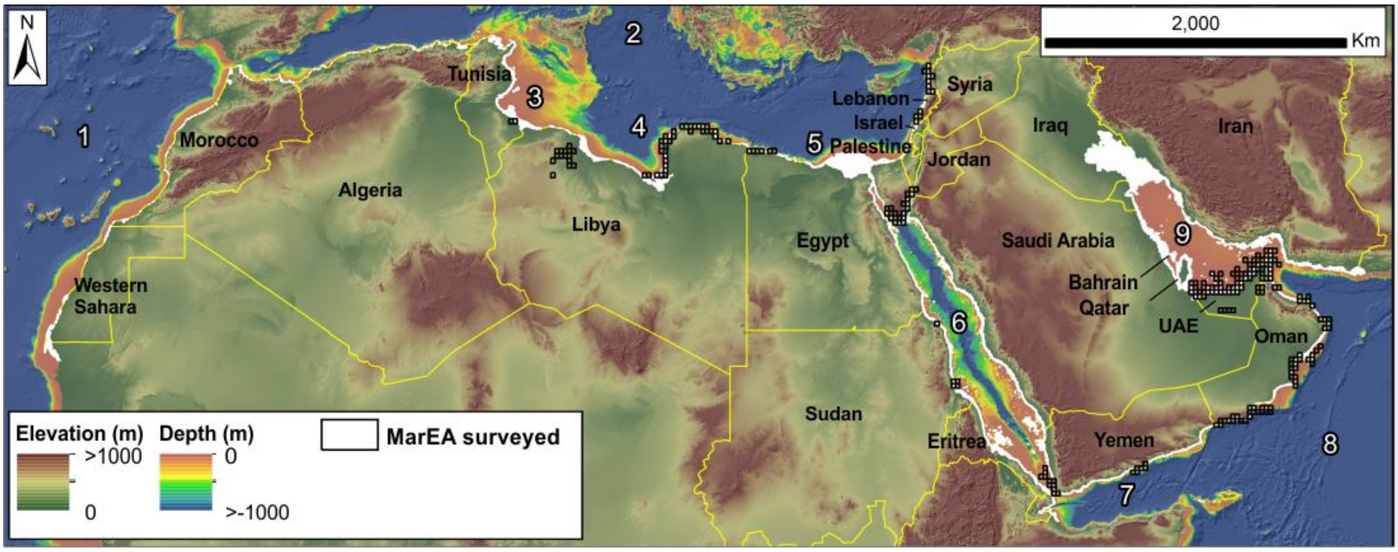

Figure 1. MENA topography, bathymetry and political geography. Elevation above sea-level is from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Farr et al. 2007)**,** depth below sea-level is from the GEBCO DEM (GEBCO Compilation Group 2019)**.** The extent of the LECZ (<10m asl) is shown in white and is derived from CoastalDEM90 (Kulp & Strauss 2019). Black grid squares show areas surveyed by MarEA and incorporated into the EAMENA database as of July 2020. Numbers indicate locations mentioned in the text: 1) Atlantic Ocean, 2) Mediterranean Sea, 3) Gulf of Gabes, 4) Gulf of Sirte, 5) Nile Delta, 6) Red Sea, 7) Gulf of Aden, 8) Arabian Sea, 9) Arabian/Persian Gulf. Yellow lines are national boundaries from the Database of Global Administrative Areas (GADM v3.6: https://gadm.org/) and do not imply any opinion, endorsement or acceptance on the part of the authors.

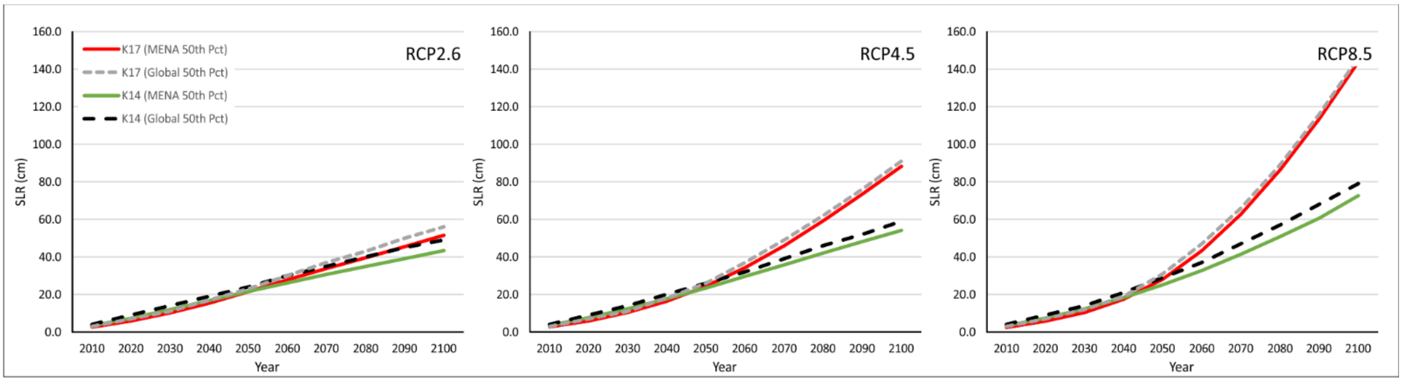

Figure 2. SLR projections for the MENA region (solid lines) compared with global projections (dashed lines) under low (RCP2.6), medium (RCP4.5) and high (RCP8.5) GHG emissions pathways. Each graph also compares model outputs from Kopp et al. (2014) (labelled K14) versus the 'pessimistic model' of Kopp et al. (2017) (labelled K17).

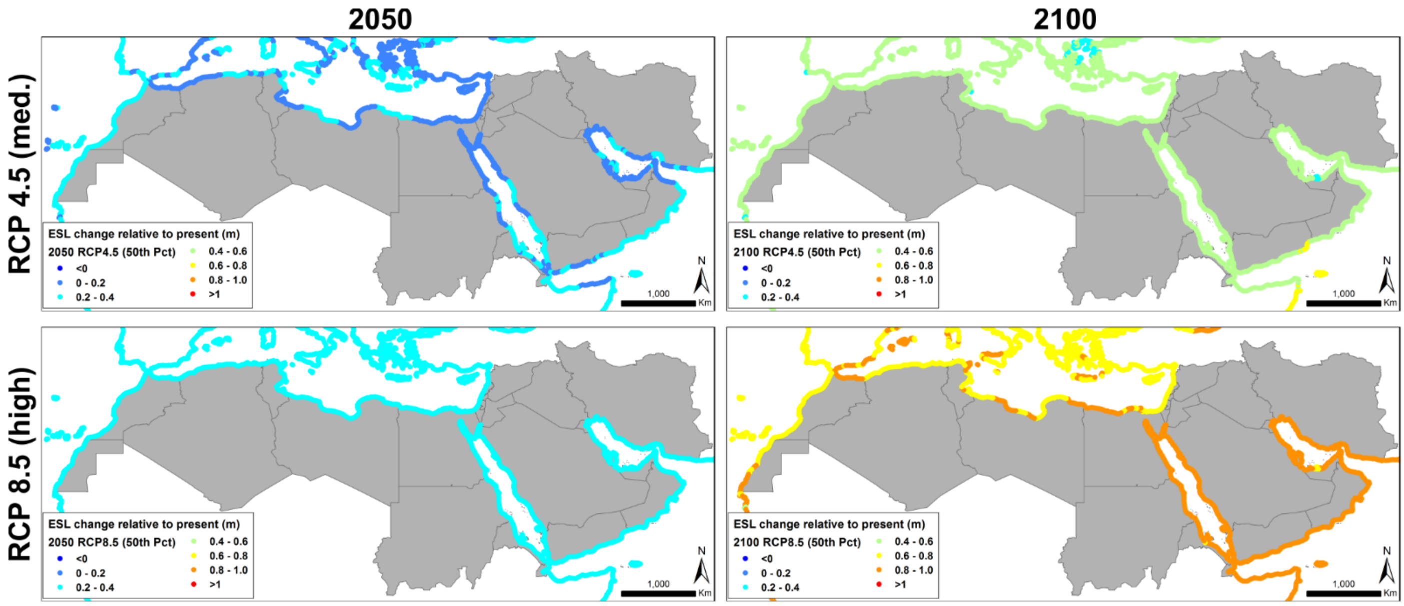

Figure 3. 1 in 100 year Extreme Sea-Level (ESL) projections presented as anomalies relative to the present day (1980-2014 baseline) for the MENA region under medium (RCP4.5) and high (RCP8.5) emissions pathways for 2050 and 2100. Data derived from the 50th percentile projections of Vousdoukas et al. (2018). International boundaries are from the Database of Global Administrative Areas (GADM v3.6: https://gadm.org/) and do not imply any opinion, endorsement or acceptance on the part of the authors.

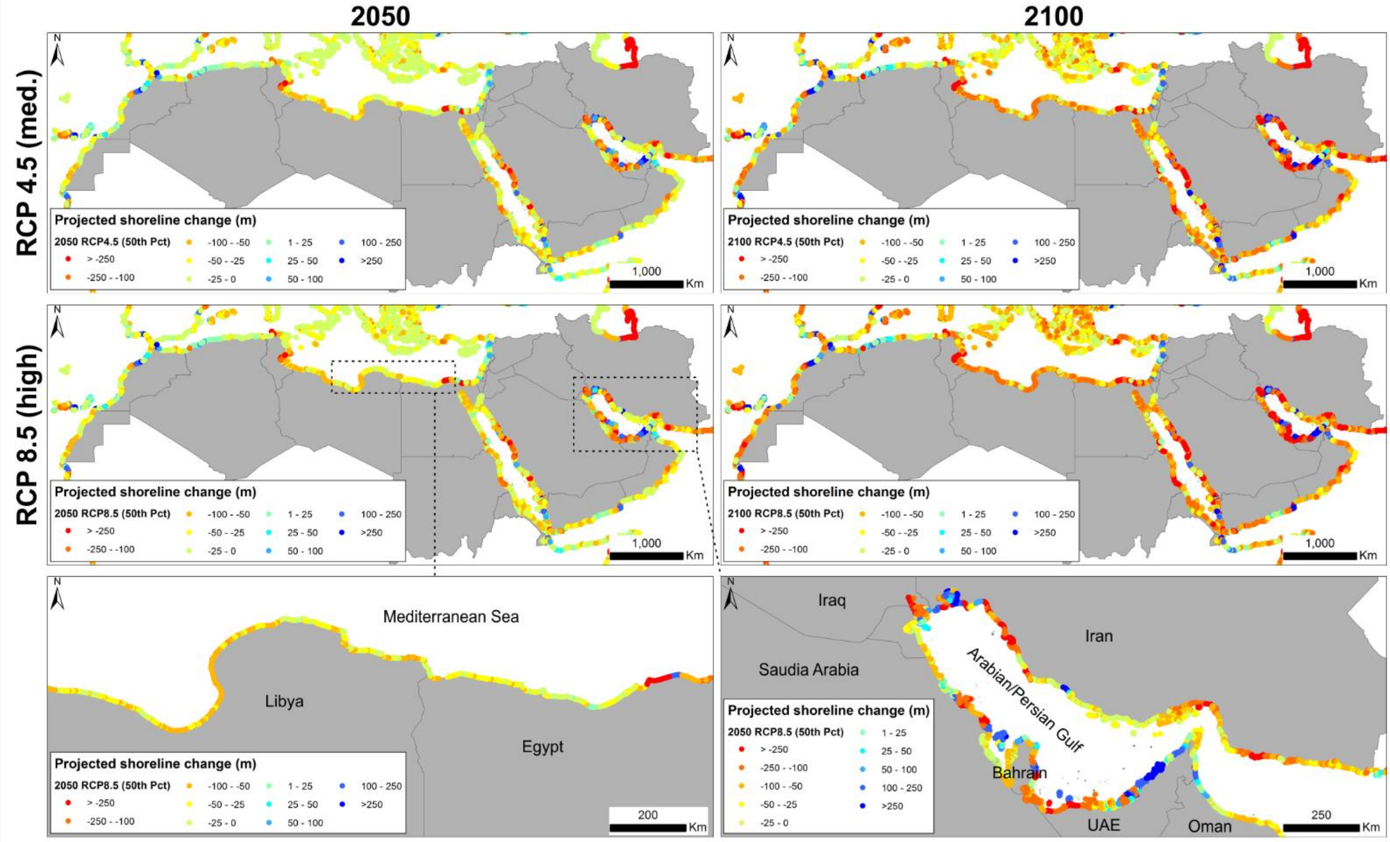

Figure 4. Shoreline change projections for the MENA region under medium (RCP4.5) and high (RCP8.5) emissions pathways for 2050 and 2100 timesteps. Warm colours and negative numbers indicate coastal retreat, cool colours and positive numbers indicate coastal advance. Dashed boxes show zoomed views of the Eastern Mediterranean (left) and Arabian/Persian Gulf (right) for RCP8.5 and 2050 in order to better demonstrate variability in projected shoreline change. Data are the 50th percentile projections from Vousdoukas et al. (2020).

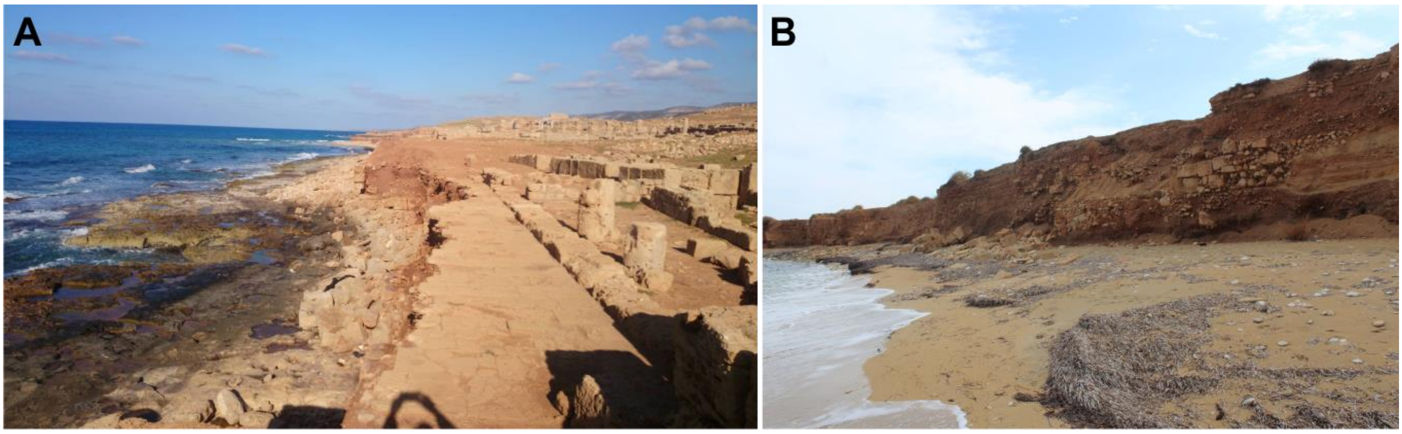

Figure 5. Impact of erosion on the coast of Eastern Libya at the sites of A) Apollonia and B) Tocra. (Photos taken November 2019 by Saad Buyadem and Saleh Alaurfi).

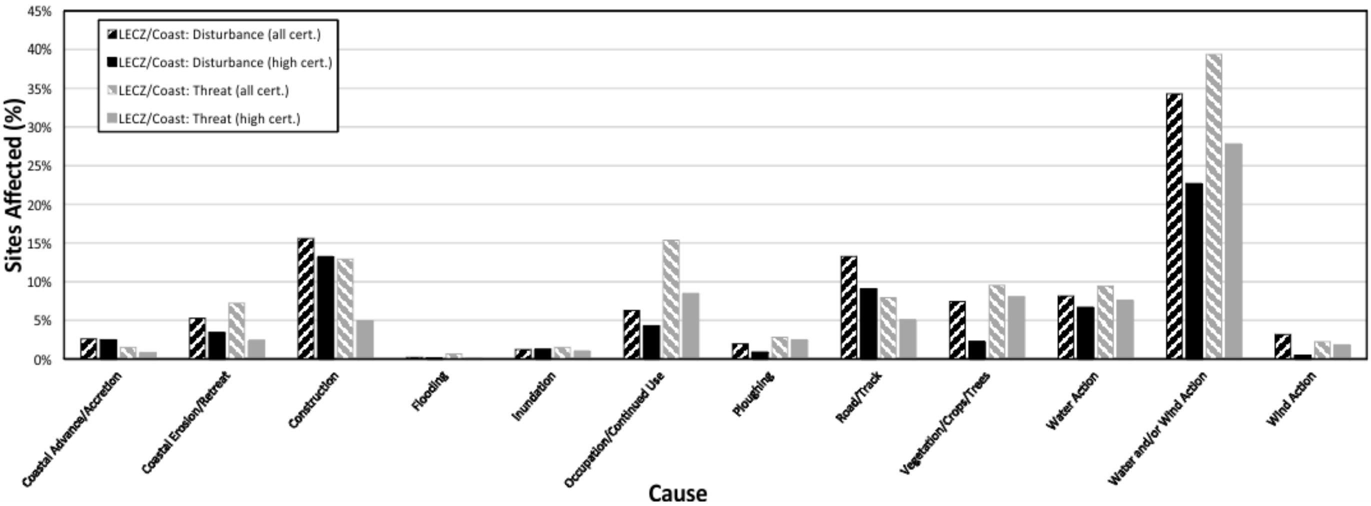

Figure 6. Percentage breakdown of documented MarEA sites for selected disturbance and threat causes. Selected causes include natural processes potentially linked to climate change, and the most common anthropogenic impact. Graph compares threat and disturbance for all certainty classes and a filtered version using only high certainty classes. See Table 2 for quantitative summary.

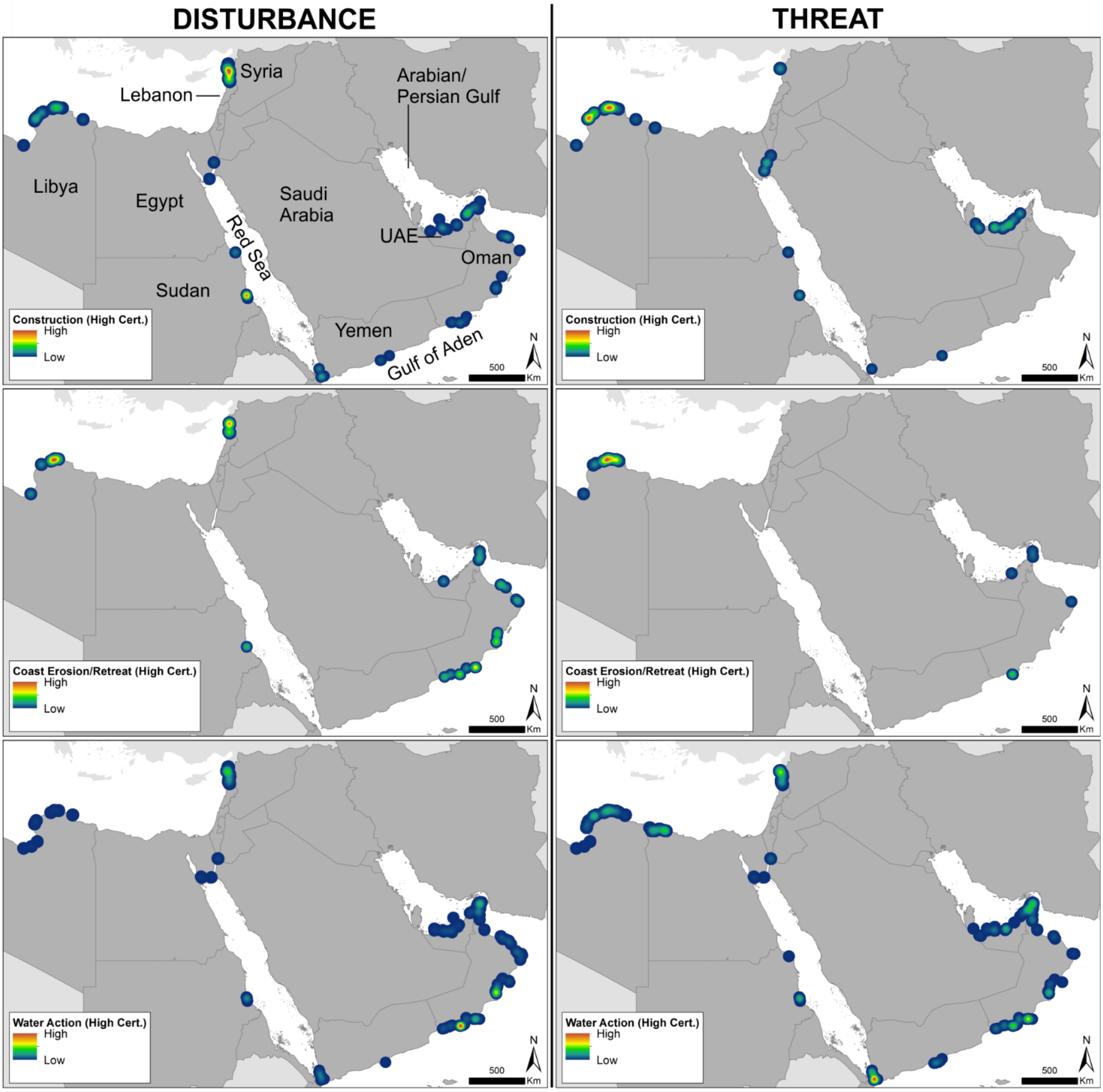

Figure 7. Coastal subset of documented sites classified under specific disturbance and threat causes. Note that in this case Water Action combines both the Water and/or Wind Action and Water Action categories in order to capture all possible instances of the impact of Water Action. Data are presented as a heat map such that High and Low values refer to site density. Colour scales have been not been normalized between images in order to highlight density per category. International boundaries are from the Database of Global Administrative Areas (GADM v3.6: https://gadm.org/) and do not imply any opinion, endorsement or acceptance on the part of the authors.

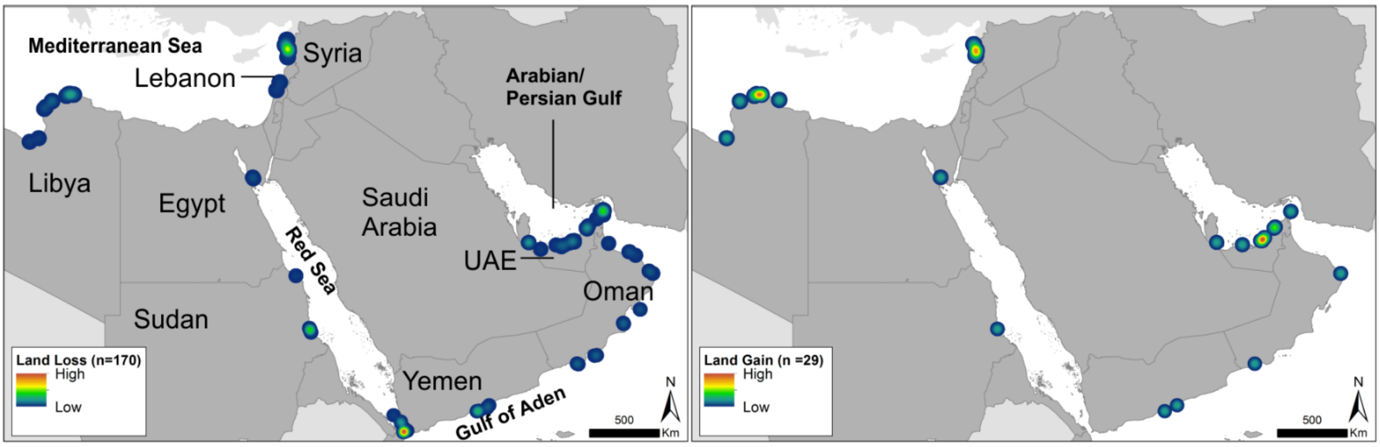

Figure 8. Coastal subset of the MarEA inventory classified according to coastal change categories from the GSW dataset. Data are presented as a heat map such that High and Low values refer to site density. Colour scales have been not been normalized between images in order to highlight density per category.

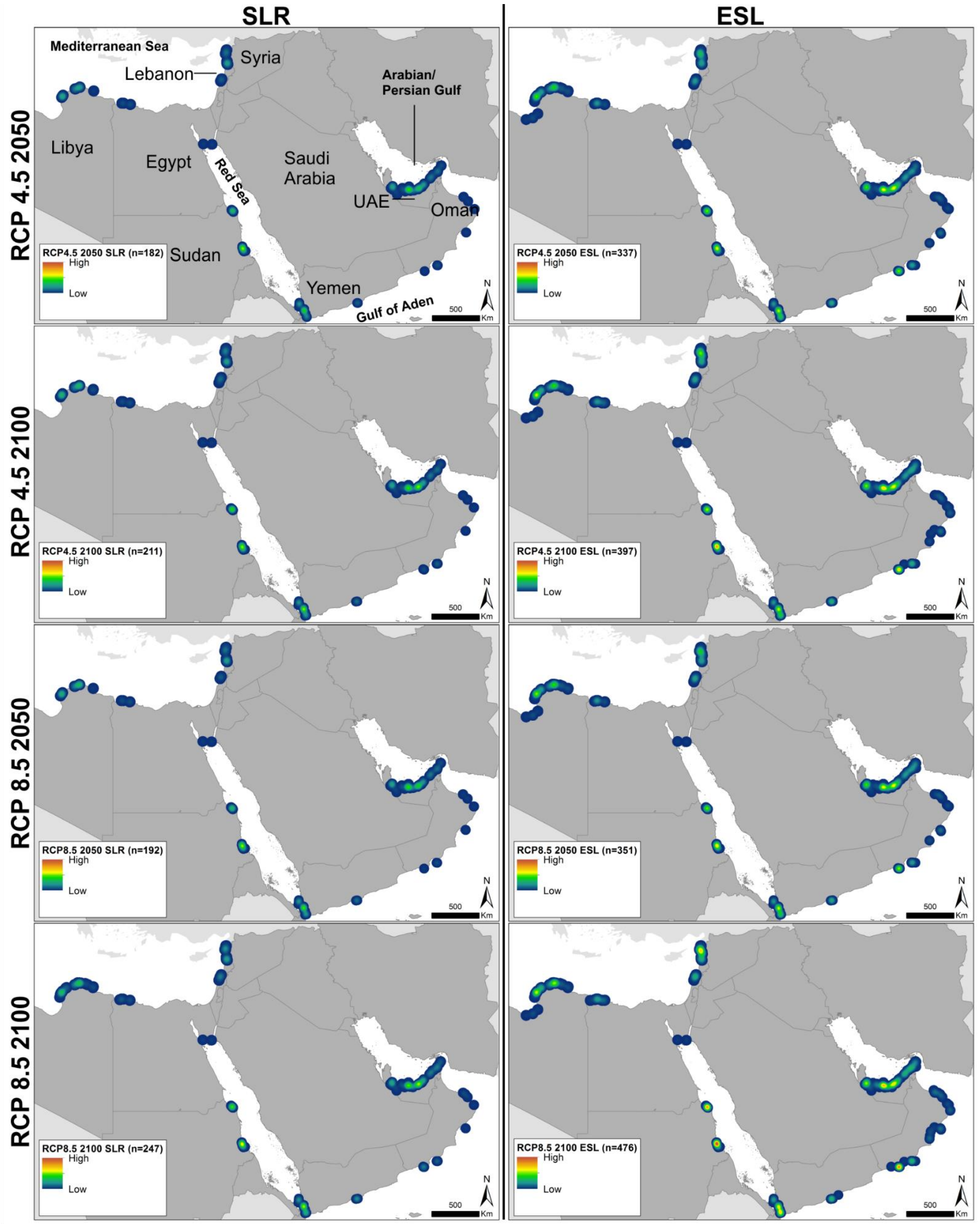

Figure 9. Coastal sites at risk from (left) long term SLR and (right) extreme sea-level (ESL) using the 50th percentile values from Vousdoukas et al. (2018). Data are presented as a heat map such that High and Low values refer to site density. Colour scales have been normalized between all images to allow comparison between RCPs and timesteps.

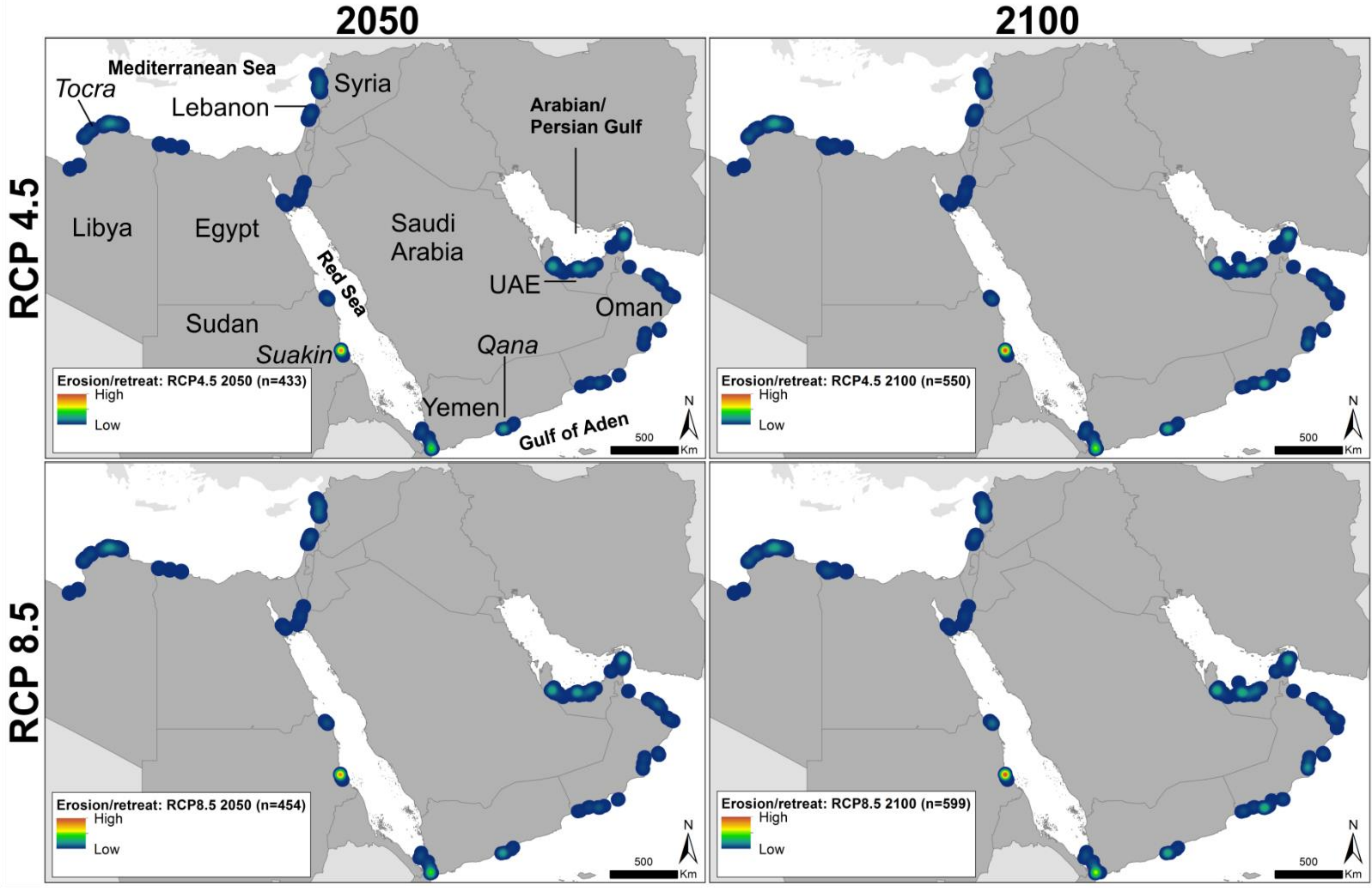

Figure 10. Coastal sites at risk of erosion based on projected shoreline retreat from Vousdoukas et al. (2020). Data are presented in the form of a heat map such that High and Low values refer to site density. Colour scales have been normalized between all images to allow comparison between RCPs and timesteps. Placenames in italics refer to sites discussed in section 7.

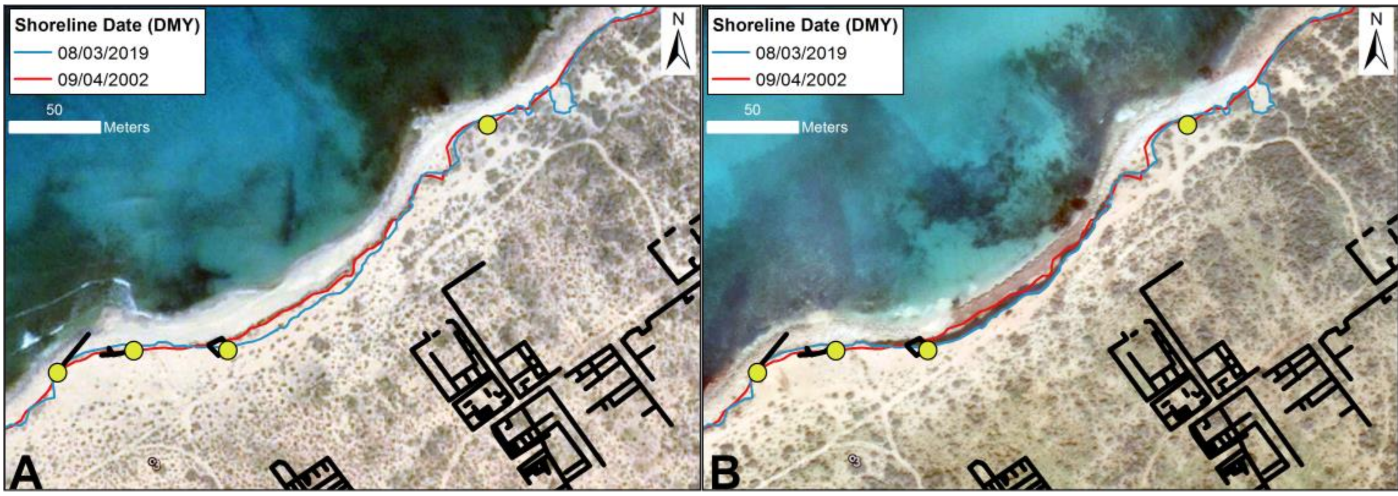

Figure 11. Google Earth satellite imagery of Tocra (Libya) from a) 2002 and b) 2019 overlain by site plan from Bennett et al. (2004). Yellow dots indicate eroding/damaged structures identified by Bennett et al. (2004). The coastal cliff edge from 2002 (red) and 2019 (blue) has also been overlain to highlight coastal retreat. See Figure 10 for site location.

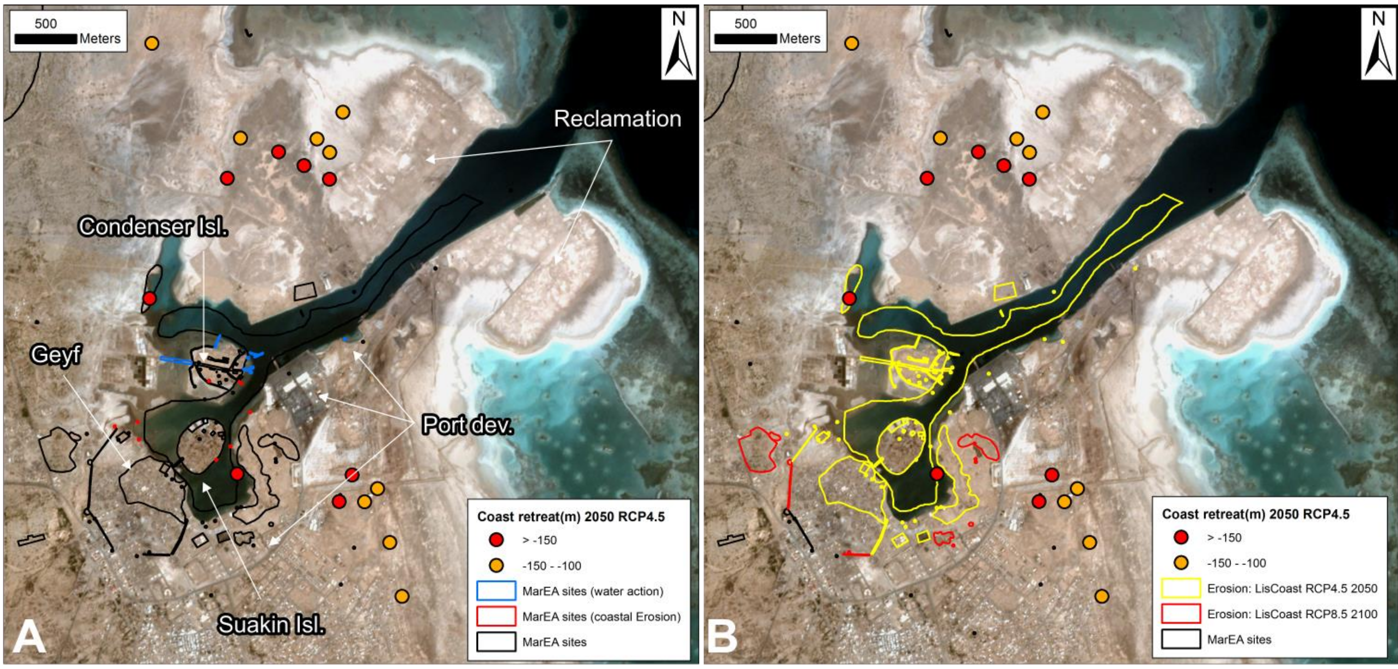

Figure 12. Projected threat at the historic port of Suakin (Sudan) based on A) MarEA documentation and B) LISCoAsT shoreline change projections. MarEA documentation shows sites projected to be impacted by coastal erosion (red polygons) and water action (blue polygons) at all certainty levels overlaid onto all documented sites (black polygons). LISCoAsT projections compare maximum (RCP8.5 2100 [yellow]) and minimum (RCP4.5 2050 [red]) numbers of sites at risk from coastal erosion/retreat. Also shown are the location of LISCoAsT shoreline change projection sites (orange and red circles) for RCP4.5 2050. Text indicates locations of port development and recent reclamation, and key areas of archaeological significance: the historic core of Islamic Suakin (Suakin island and the Geyf) and centre of British colonial operations (Condenser Island). See Figure 10 for site location. Underlying satellite image dates from 10/09/2019 and is from Planet Team (2017).

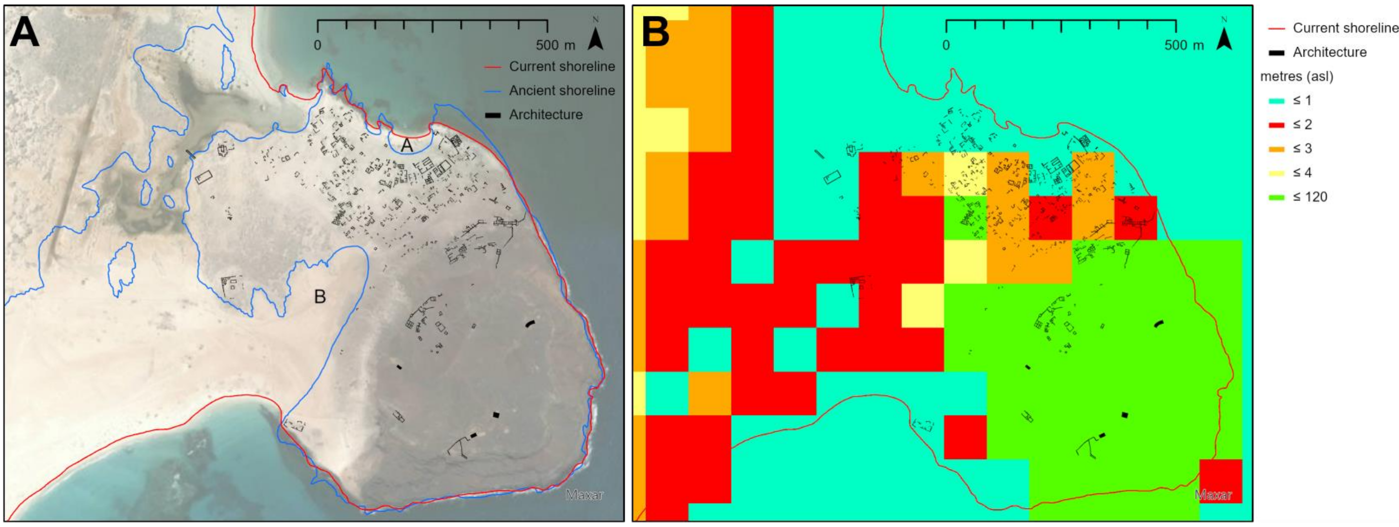

Figure 13. A) Site plan of Qana/Bir ‘Ali (Yemen) indicating its main architectural surface features, current and ancient shoreline, and silted up harbours (A and B). Adapted from Mouton et al. (2006, Figures. 5 and 10) with permission; copyright Persée (https://www.persee.fr/). Base map: GeoEye-1 satellite image (Maxar and Google Earth). B) Classified digital terrain model (CoastalDEM90) overlying the Qana site plan, indicating elevations most at risk from sea-level rise and extreme sea-levels (≤1 and ≤2m asl). See Figure 10 for site location.

S1 Supplementary Information: Documentation and Data Processing Methods

This supporting section describes the methods underpinning the analysis presented in the main text. Sub-sections below cover: 1) MarEA disturbance and threat documentation procedure; 2) Pre-analysis processing of the MarEA data; 3) Integration of MarEA data with the Global Surface Water (GSW) dataset; 4) Integration of MarEA data with the Large Scale Integrated Sea-level and Coastal Assessment Tool (LISCoAsT) sea-level and CoastalDEM90 datasets; and 5) Integration of MarEA data with the LISCoAsT shoreline change dataset.

1. MarEA disturbance and threat documentation

Documentation is based primarily on assessment of VHR (Very High Resolution: <1m) satellite imagery for site identification, condition assessment and landscape characterisation, supplemented by extant grey and peer-reviewed literature, marine geophysical data and in situ visits where/when available. All sites documented by MarEA are deposited on the open access EAMENA database hosted by the University of Oxford (https://database.eamena.org/). The basic documentation procedure is as follows:

1) Each site is geolocated on VHR satellite imagery. This can be based either on direct identification of archaeological remains visible on the imagery or, where remains are not visible, from external information resources. For example, published coordinates or location descriptions. Certainty qualifiers (e.g. Definite-High-Low-Medium) provide an assessment of the accuracy of the recorded site location
2) Descriptive information about the archaeological remains is recorded into the database, either directly entered or entered into spreadsheets for subsequent bulk uploads. This information includes site shape, the form of identifiable features, site function, site interpretation and cultural period.
3) The location is then examined using a time-series of satellite imagery. The availability and length of time-series depends on the location. Some areas are covered by extensive image series in Google Earth which cover the last ~20 years, other sites may only have a handful of recent images. Where possible, the time series is extended using historic spy satellite imagery (e.g. Corona) dating back to the 1960-70s.
4) Disturbances identifiable from the satellite imagery which impact the archaeological site are recorded into the database. Information pertaining to each disturbance includes generalized disturbance category, specific disturbance cause, certainty of the disturbance cause, date of disturbance, effect of the disturbance and the present/latest known condition of the site. For example, the analyst might observe coastal erosion/retreat impacting a site over the past 10 years and resulting in collapse/structural damage to the archaeological remains and which has impacted 11-30% of the site. This can also be also supplemented by external information resources where available, such from published or grey literature. For example, reports could indicate that coastal erosion has also impacted the archaeological site prior to the start of the available imagery time series.
5) Threat assessment is then based on the trends observed by the analyst directly from the imagery, or based on external information resources. Information pertaining to each threat includes generalized threat category, specific threat cause and likelihood of each cause. For example, the analyst might determine based on the imagery or external information resources that coastal erosion will continue into the future, and thus present a probable threat to the archaeological site. Alternatively, they may also know from reports that a particular location

will be developed into a modern harbour, thus threatening archaeological sites via building/development.

6) For all the above steps, standardization of terminology is maintained by fixed fields with dropdown menus populated by a controlled vocabulary. In addition, many fields are linked to certainty categories which are used account for any uncertainty in the analysts' assessment. These take the form of Definite-High-Medium-Low classifications, with the exception of the threat assessment which uses a Planned-Probable-Possible classification.
7) For the dataset presented here, all documentation was done remotely by the MarEA team members who are based in the UK. However, this will change over the next few years as remote documentation is supplemented by field surveys conducted by in-country partners (see example projects on the MarEA website: https://marea.soton.ac.uk/).

Further details on the MarEA project can also be found in Andreou et al. (2020) and additional detail on the documentation procedure and EAMENA database can be found in Rayne et al. (2017).

2. Pre-analysis processing of MarEA data

As of July 2020, 5609 sites were documented by MarEA team members and available on the EAMENA database. Data can be downloaded in table form (.csv) and in GIS-compatible shapefiles (.shp). Both types were used in this analysis. Tables were used to quantify threat/disturbance based directly on the MarEA documentation and generate graphs (main text sections 4.1, 5.1). Shapefiles were used for geospatial integration with other models (main text sections 4.2; 5.2; 5.3; 6) and for general mapping purposes.

A subset of 1386 'coastal' sites filtered out of the overall MarEA data was used for the analysis presented here. Coastal, as defined here, comprises all sites within the Low Elevation Coastal Zone (LECZ: land <10m in elevation and in hydrological connection to the sea) or on the shoreline. Several filtering steps were employed using a combination of geospatial location and terms entered into each record (site) during the process of documentation.

Key fields containing these terms are:

- Topography: records one or more descriptors of the documented site's topographic setting.
- Location Certainty: records level of certainty of the accuracy of the documented site's location as entered into the database

Filtering steps to obtain the coastal subset comprised:

1. Positional accuracy check: only records with Location Certainty field containing terms 'Definite', 'High', 'Medium' were included
2. Removal of fully subtidal sites: records where the Topography field contained only the topographic descriptor Ocean/Sea Bed (subtidal) were excluded
3. Inclusion of LECZ sites: all sites with polygons intersecting the LECZ of the CoastalDEM90 database were included
4. Inclusion of non-LECZ coastline sites: all sites outside the modelled LECZ but containing within the Topography field the following coastal topographic descriptors were included:
    - 'Ocean/Sea Shore', 'Bay/Inlet', 'Beach', 'Coast (linear/straight)', 'Coastal Cliff', 'Delta', 'Estuary', 'Intertidal Flat', 'Island/Islet' or 'Reef'.

Additional filtering was employed for the quantification of documented threat and disturbance causes, specifically to provide a certainty-filtered variant of the coastal subset. This was based solely on the information documented for each record. Key fields containing relevant terms are:

- Disturbance Certainty: records the level of certainty of the investigator's interpretation of observed causes of disturbance affecting the documented site.
- Threat Probability: records the level of certainty of the investigator's interpretation of likely types of threats which might affect the documented site

The following data subsets were used:

1. All threat/disturbance certainties: no filtering applied.
2. High certainty disturbance causes: only records with Disturbance Certainties field containing terms 'Definite' or 'High' were included
3. High certainty threat causes: only records with Threat Probability field containing terms 'Planned' or 'Probable' were included

3. Integration with Global Surface Water dataset

Past disturbance was estimated by comparing locations of MarEA documented sites against coastal changes identified from the open source Global Surface Water dataset (GSW: Pekel et al. 2016). GSW was developed to quantify the spatial extent of water gained or lost from the Earth surface over the past 30 years using satellite imagery. In the coastal zone, losses can result from multiple causes including result of natural sediment accretion, anthropogenic land reclamation, infill or draining of wetlands and the diversion or covering of water bodies. Surface water gain could result from natural erosion, anthropogenic shoreline modification (e.g. dredging), flooding of wetlands or creation of reservoirs and ponds. The application of GSW to shoreline change research was further developed by Mentaschi et al. (2018) who developed additional coast-specific classifications:

3. Land Loss: Land converted to sea/intertidal zone (coastal retreat proxy)
4. Land Gain: Sea/intertidal zone converted to land (coastal advance)

Sites were classified as impacted by coastal change if their spatial boundary intersected with one of the aforementioned coastal change categories. Since GSW data is hosted on the Google Earth Engine (GEE: Gorelick et al. 2017) cloud computing platform, it was used to integrate the MarEA data with GSW. Workflow steps were as follows:

1) MarEA data in shapefile format were ingested to GEE. Shapefile exports from the EAMENA database are separated by geometry (point, line, polygon), thus point and line data were converted to polygons allowing all MarEA data to be merged as a single polygon feature class.
2) Merged MarEA data were filtered using the locational and coastal filters described above.
3) GSW v1.1 data were imported and re-classified in GEE into the above coastal categories. Each coastal change category (e.g. Land Loss, Land Gain) was separated out as an individual Boolean raster.
4) In GEE, ReduceRegions was applied to each reclassified GSW coastal change raster using the MarEA data as input, and a maximum reducer. This identified if any of the coastal change class fell within the boundary of each MarEA site polygon and appended this information to its attribute table.
5) Updated MarEA subsets were then exported as shapefiles for quantification and in ArcGIS 10.3. For display purposes, the polygon shapefiles were converted to points for processing into Kernel Density rasters (heat maps)

4. Integration with CoastalDEM and LISCoAsT sea-level

Threat assessment of flooding was based on obtaining present elevations above sea-level of each MarEA site and comparing these against projections of future Sea-Level Rise (SLR) and Extreme Sea-

Level (ESL). Site were classified as impacted by SLR or ESL if these projected values exceeded the present mean elevation of the site. Present elevation values were obtained from the CoastalDEM90 dataset (Kulp and Strauss 2019), SLR and ESL were obtained from the open source LISCoAsT Global Extreme Sea-level projections dataset (Vousdoukas et al. 2018a; Vousdoukas et al. 2018b). A combination of GEE and ArcGIS 10.3 were used for processing. Workflow steps were as follows:

1) MarEA data was ingested into GEE, processed and filtered using the locational and coastal filters described above.
2) The CoastalDEM90 dataset covering the MENA region was ingested into GEE and processed to find the LECZ.
3) In GEE, ReduceRegions was applied to CoastalDEM90 using the MarEA polygon data as input, and a mean reducer. This identified the mean elevation of each MarEA site polygon and appended this information to its attribute table.
4) Updated MarEA data were filtered by the CoastalDEM90 LECZ to exclude sites located in areas which are not in hydrological connection to the sea (i.e. low-lying sites away from the coast which are not at risk of coastal flooding).
5) The resulting MarEA data (elevation updated, filtered by LECZ) were exported as shapefiles for further processing in ArcGIS
6) LISCoAsT projections were imported into ArcGIS. These data comprise a series of point locations attributed with projections of SLR and ESL at specific timesteps and RCPs. For this study, the 50th percentile values of SLR and ESL at 2050 and 2100 timesteps under RCPs 4.5 and 8.5 were used.
7) In ArcGIS, a Spatial Join was applied to the MarEA data in order to obtain, for each documented site, the SLR and ESL values from the closest LISCoAsT data point.
8) The difference between CoastalDEM90 elevation, SLR and ESL values was then calculated for each documented site. If a site is located on land/on the coast and SLR or ESL exceeded the CoastalDEM90 elevation, this was classified as impact. Sites were quantified accordingly by RCP and timestep.
9) For display purposes, the final polygon layers were converted to points for processing into Kernel Density rasters (heat maps)

5. Integration with LISCoAsT shoreline change

Threat assessment of erosion was based on comparing the present distance to the shoreline of each MarEA site against shoreline change projections. Sites were classified as impacted by coastal erosion/retreat if the projected distance of landward shoreline movement exceeded the present distance to the shore of the site. Present distances to the coast were calculated using the open source Open StreetMap (OSM) shoreline and the shoreward-most point of each site's boundary. Shoreline change distances were obtained from the open source LISCoAsT Global Shoreline Change projections dataset (Vousdoukas et al. 2020; Vousdoukas et al. 2019). ArcGIS 10.3 was used for all processing. Workflow steps were as follows:

1) MarEA data (processed and filtered as in step 1 for both of the previous examples) was imported into ArcGIS.
2) In ArcGIS, the Near tool was run on the MarEA data and the OSM shoreline to find the present distance from each site to the shoreline.
3) LISCoAsT Global Shoreline Change projections were imported to ArcGIS. These data comprise a series of point locations attributed with projections of shoreline movement at specific percentile values, timesteps and RCPs. For this study, the 50th percentile values at the 2050 and 2100 timesteps under RCPs 4.5 and 8.5 were used.

4) A Spatial Join was run between the MarEA data and the LISCoAsT projections in order to obtain for each documented site the projected shoreline movement values from the closest LISCoAsT data point.
5) The difference between projected shoreline movement (50th percentile) and present distance to the shoreline was calculated for each documented record. If a site was located on land/on the coast and the projected coastal retreat exceeded the present distance to the shore, this was classified as impact from erosion.
6) For display purposes, the final polygon layers were converted to points for processing into Kernel Density rasters (heat maps).

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