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Exploring the Impact of Tropical Cyclones on Oman's Maritime Cultural Heritage Through the Lens of Al-Baleed, Salalah (Dhofar Governorate)

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Abstract

Tropical cyclones are among the most detrimental hazards to the environment, societies, and economies, each year affecting millions of people and resulting in substantial casualties and material destructions in coastal communities. In this context, maritime cultural heritage, encompassing material evidence for the engagement of people with the sea, both on land and under water, is particularly vulnerable. Despite the significant number of archaeological sites exposed to tropical cyclones and other extreme sea-level events, maritime cultural heritage in the MENA region is rarely included in coastal vulnerability indices or incorporated in mitigation strategies, disaster management, sustainability, and resilience policies. In this study we examine the impact of tropical cyclones on the maritime archaeology of Oman with emphasis on the Dhofar region. This paper builds on existing coastal research in the Dhofar region—an area identified as the most cyclone-prone administrative region in Oman, but also an area that contains substantial archaeological remains. Central among Dhofar's maritime cultural heritage is Al-Baleed, a Medieval seaport with unparalleled evidence of engagement with international trade networks.

Keywords Maritime archaeology · Tropical cyclone · Oman · Arabian Peninsula

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Introduction

Climate change and increasing global sea-level rise are widely considered factors negatively affecting coastal communities, societies, ecosystems, and economic sectors. Originating in the Indian Ocean, tropical cyclones have left their footprint on the Arabian Peninsula (Webster et al. 2005; Fritz et al. 2009; Mohanty et al. 2013; Hereher 2020 for summary of research), occurring during the pre-monsoon (May) and post-monsoon (October, November) seasons. The increasing frequency of cyclones (Knutson et al. 2010; Walsh et al. 2016; Wehner et al. 2019) and associated high storm surge, have been viewed in conjunction with climate change (Ahmed and Choutri 2012; Al-Awadhi et al. 2019; Hereher et al. 2020; Mansour et al. 2021), alongside other phenomena, including higher temperatures, more frequent rainfall, and extreme storms (see inventory: IBTrACS—International Best Track Archive for Climate Stewardship (unca.edu)). Increases in the sea-level, even at small rates, are estimated to have a significant impact on low-lying coastal areas, especially when combined with storm surges and flooding (Muis et al. 2016; Vousdoukas et al. 2018; Al Ruheili and Radke 2020:502; Hereher et al. 2020).

The geographic location of Oman, combined with its arid to semi-arid climate, makes it prone to chronic water stress, prolonged drought, and flooding, all of which contribute to its coastline's vulnerability to extreme climate events, such as cyclones and tsunamis (Fig. 1). The southern coast of Oman is exposed to cyclones every five to seven years (Mansour 2019:12), and these phenomena are anticipated to escalate in the next few

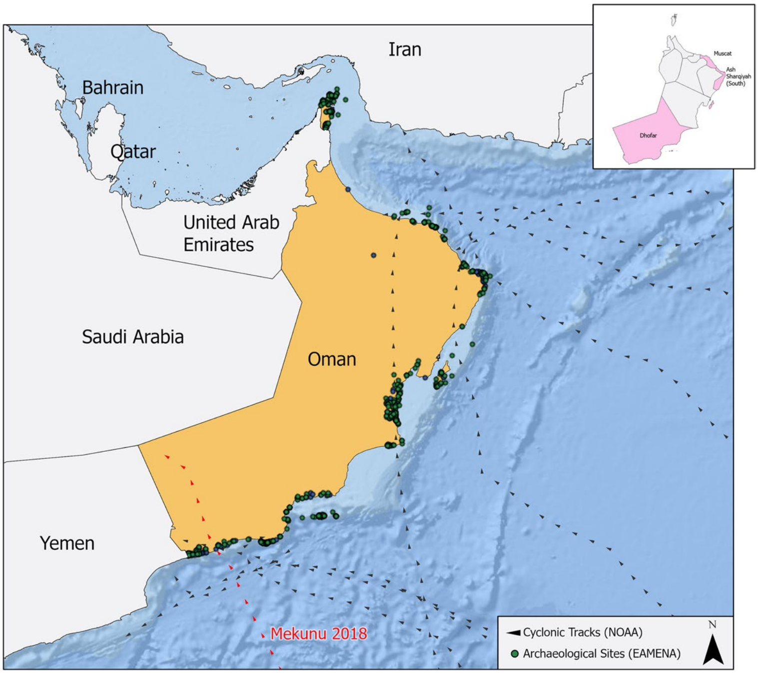

Fig. 1 Map of Oman showing historic cyclone tracks in conjunction with archaeological sites documented by MarEA and stored in the EAMENA database (produced on ArcGIS Pro with information from the National Hurricane Center, National Oceanic and Atmospheric Administration)

decades with an estimated increase in temperature of 2°–5° between 2041 and 2060 and higher precipitation in the Dhofar region (Al Wardy et al. 2016). This is further attested in diachronic comparisons of the economic and infrastructural impact of recent cyclones such as the ARB01 of 2002, Gonu of 2007, Phet of 2010, Keila of 2011, Ashobaa of 2015, and Mekunu of 2018 (Gunawardhana et al. 2018; Al-Awadhi et al. 2019; Al Ruheili and Radke 2020:503). Based on this increasing exposure to more frequent and intensified storm surges, some scholars have placed Oman in the top ten developing countries to be significantly impacted by cyclone activity (Dasgupta et al. 2009). Emphasis was also placed on the problematic relationship between the expansion of impervious surfaces such as concrete (typical of urban environments) and limited resilience to the environmental changes associated with cyclones, such as increased precipitation and flooding (Al-Awadhi et al. 2016; Al-Awadhi et al. 2019). This relationship was particularly evident in the recent (3 October 2021) cyclone Shaheen, causing extensive flooding in Muscat (Shaheen: Tropical cyclone batters Oman and Iran, killing 13—BBC News).

The National Oceanic and Atmospheric Administration (NOAA; Historical Hurricane Tracks) has documented 36 hurricanes affecting the coastline of Oman in the past 129 years. Following the Saffir-Simpson Hurricane Wind Scale (The Saffir-Simpson Team 2019), these hurricanes have been classified in five categories. Hurricanes with sustained winds of over 150 mph are described as tropical cyclones. It is important to note that known cyclones, such as Mekunu (2018), had a maximum speed of 100 knots (kt) (about 115 mph), which is lower than the threshold used in the Saffir-Simpson Wind Scale. This discrepancy likely suggests different perceptions of the impact of strong winds between those classifying wind speed and those experiencing the impacts of these events (see also Camelo and Mayo 2012). Conceptual variabilities can also be observed in the definition of cyclones used by the National Centers for Environmental Information as wind with a speed higher than 74 mph.

Scientific research (geology, coastal science, climatology, urban planning, etc.) on tropical cyclones on the Arabian Peninsula has focused, among others, on improving forecasting and simulating (e.g. Li et al. 2021), identifying isotopic signatures (Müller et al. 2020) and fostering a deeper understanding of the cyclone cycle (e.g. Wang et al. 2012; Hafez 2017; Chowdurry et al. 2020). Existing research on the impact of cyclones has focused on developing coastal sensitivity indices (e.g. Al-Hatrushi 2013; Al-Hatrushi et al. 2015; Al-Awadhi et al. 2020) and vulnerability models (Hereher et al. 2020), modelling the impact of sea-level rise (SLR) and flooding (Al Ruheili and Radke 2020; Banan-Dallalian et al. 2021) and applying probabilistic-based methods, the results of which have informed decision making for damage mitigation and management. For example, analysis of flash flood impact following cyclone ARB02 (2008) in south central Yemen has resulted in recommendations in terms of the application of water diversion structures and agricultural land use practices (Alga'fari 2014).

Due to the role of the coast in the economy of Oman, substantive research has been conducted on flood risk (Al-Awadhi et al. 2017), sea-level fluctuations (Al-Awadhi et al. 2020), and coastal erosion (Al-Hatrushi et al. 2014), including the collection of high-water marks (Fritz et al. 2009). In these discussions, tropical cyclones are generally understood as factors impacting the environment, infrastructure, and economy of affected areas. As such, despite historical and geoarchaeological evidence for the impact of ancient cyclones (e.g. Hoffmann et al. 2015; Ermertz et al. 2019; Newton and Zarins 2019:118; Al Ruheili and Radke 2020) and other extreme sea-level events such as tsunamis (Donato et al. 2008; Hoffmann et al. 2013, 2020), research on vulnerable maritime archaeological sites in Oman is limited. This could be related to a challenged, yet longstanding conceptual division between natural and cultural heritage (Harrison 2015), which is evident in research and policies on natural and cultural heritage preservation (Breen et al. 2021). Moreover, as the coast of Oman is home to over 60% of the country's population and the base for profitable sectors including tourism and trade (Al Ruheili and Radke 2020:503), it is reasonable to assume that the social and economic value of the Omani coastline derives more from those factors and less from its rich cultural heritage.

Among the regions identified as the most vulnerable to the impacts of tropical cyclones, are areas with a high density of maritime cultural heritage. These regions include, for example, the Dhofar Governorate on the South (Mansour 2019; Newton and Zarins 2019) and the Muscat and Ash Sharqiyah Governorates on the NE coast of Oman (Mansour et al. 2021). The latter includes important sites such as Qalhat (Vosmer 2004; Rougeulle 2010), Ras al-Hadd (Fritz et al. 2009), and Sur (Banan-Dallalian et al. 2021)—all affected by Gonu of 2007, which has been described as "the strongest cyclone that occurred in the Arabian Sea" (Hereher 2020:2). Following the detrimental effect of Gonu, the Sultanate of Oman took significant measures (dam construction, road network restructuring, raising awareness) to minimize the number of casualties and material damages which, as a result, were relatively fewer when Oman was hit by Phet in 2010 (described as the second largest cyclone in the Arabian Sea, Hereher et al. 2020:369) and by Mekunu in 2018. Though such initiatives offer opportunities to examine the impact of cyclones on archaeological sites (see e.g. Andreou et al. 2022:142–143), cultural heritage does not appear to be incorporated in mitigation and management strategies.

Maritime Cultural Heritage in Oman

Oman, possessing 3165 km of shoreline stretching from the Strait of Hormuz to the border with Yemen, is a country with an extensively documented historical engagement with the sea. Oman's rich maritime history and archaeology is well documented with evidence of marine resource exploitation as early as the Neolithic age (Beech 2004), and historical references to the land of "ichthyofagi" (fish eaters) that corresponds to the southern Arabian peninsula and probably includes Oman (Arrian, Indica; Anon, Periplus Maris Erithraei). There are also records showing the establishment of Medieval harbours as part of the maritime silk roads (Winter 2020) and a longstanding boat building tradition (Agius 2002). Due to the density and diversity of the available material evidence along its coast, different scopes of investigation have been employed across Oman, with some instances of country-wide documentation (Biagi 1988; Blue et al. 2016). A wide array of maritime archaeological sites and features have been documented (shell middens, shipwrecks, abandoned ships, iconography, settlements, cemeteries, and harbours), each with distinct challenges in preservation. A number of sites are presently inventoried in the EAMENA database (database.eamena.org), including information on chronology, visible features, and associated disturbances and threats (Andreou et al. 2022).

The present study employed the methodology of site documentation as outlined in the introductory paper by Breen et al. (see also Andreou et al. 2020) to document and assess threats to maritime archaeological sites across the coastline of Oman. This methodology combines published historical and archaeological information (excavations and surveys), with new evidence identified through close examination of publicly available (Google Earth Pro) and purchased (PlanetScope) satellite imagery. So far, 1572 archaeological observations have been documented across the coastline of Oman, 1055 of which

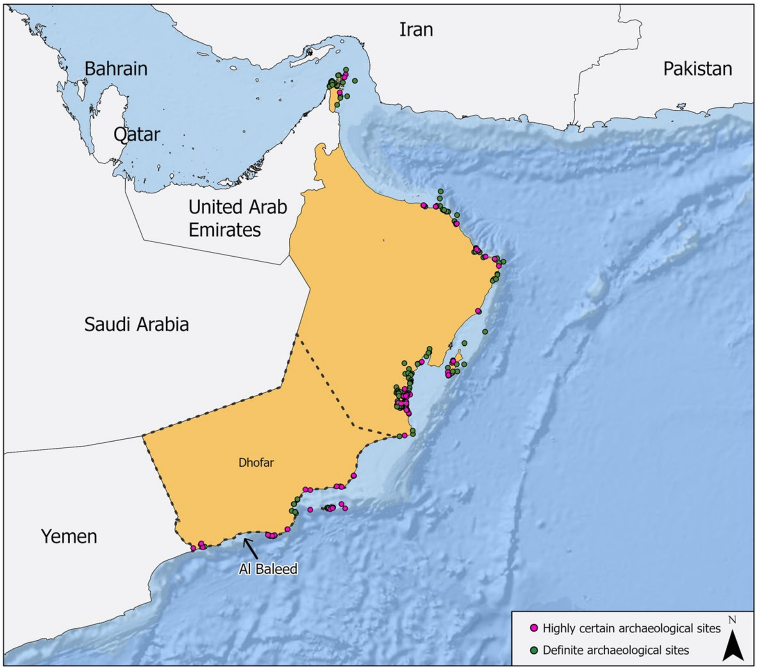

Fig. 2 Map showing archaeological sites uploaded in the EAMENA database with "definite" and "high" archaeological certainty (produced on ArcGIS Pro)

are presently stored in the EAMENA database (Fig. 2). These observations range from small figures, such as anchors, traditional boats, and fishing huts, to large and extensively examined settlements such as Qalhat and Al-Baleed. Following an observation certainty classification built into the EAMENA database, with values such as "Definite", "High", "Medium", "Low", and "Negligible", it is important to note that 352 sites have a definite archaeological certainty value and 295 have a high archaeological certainty value.

Within the Dhofar Governorate, which is identified as very vulnerable to tropical cyclones, 316 sites are currently inventoried in the EAMENA database, 57 of which with definite archaeological certainty and 109 with a high (Fig. 3a–b) certainty. Due to its location, variety of material remains, and definite archaeological value, the site of Al-Baleed and its broader maritime cultural landscape lends itself well to conducting a detailed threat assessment (in this case on cyclone impacts) using multiple lines of remote sensing evidence.

Al-Baleed, Dhofar Governorate

The Dhofar Governorate is located at the border with Yemen, at the south of Oman. It has been identified by coastal scientists and geographers as the most cyclone-prone area in Oman (Al Ruheili and Radke 2020:505, Table 1). The severe impact of cyclones in Dhofar has been taken into consideration in master plans on sustainable development and resilience, especially after the catastrophic cyclone of 2002 (Al-Hakmani 2002). Despite

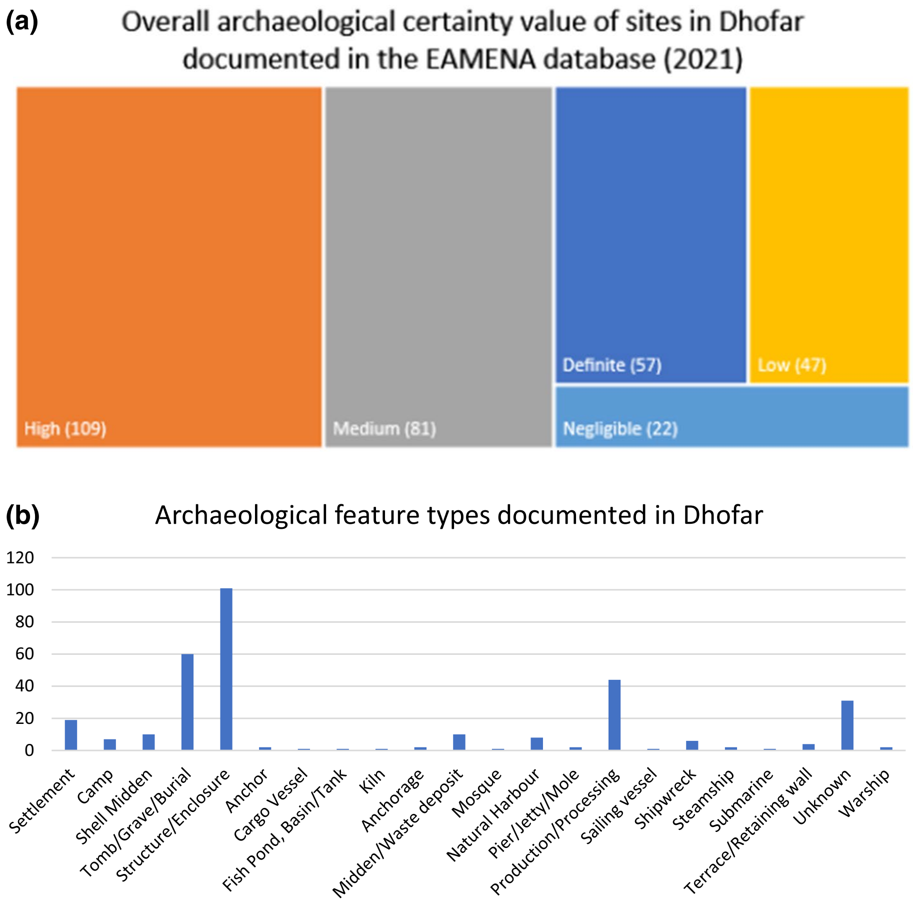

Fig. 3 **a** Overall archaeological certainty value of sites in Dhofar documented in the EAMENA database (as of October 2021) (produced on Excel). **b** Archaeological feature types in Dhofar documented in the EAMENA database (as of October 2021) (produced on Excel)

Dhofar's vulnerability, the area was not subjected to cyclone risk assessment until 2019 (Mansour 2019). Moreover, Al Ruheili and Radke (2020:511, Fig. 5) have modelled Dhofar's inundation based on sea-level rise and precipitation data from May 2002 and visualized the affected areas, often up to 400 m from the sea. Coastal vulnerability maps produced by Hereher et al. (2020:368, Fig. 6) highlighted Salalah, particularly the area between the sites of Al-Baleed and Khor Rori (Avanzini 2008), as highly vulnerable to sea-level rise and the associated impacts of cyclones and tsunamis. Among the parameters factored in Hereher et al. (2020:638, Fig. 6) CVI are coastal geomorphology (sandy beaches are more vulnerable), the elevation of the coast (the lower, the more vulnerable), the slope of the coast (the more gentle, the more vulnerable), bathymetry and tidal patterns.

Al-Baleed or ancient Ẓafār was an international port on the NW Indian Ocean, the earliest material evidence of which dates to the tenth century Common Era (CE) (Pavan et al. 2020, Figs. 2 and 4). The present location of the early city is approximately 120 m from the water. Most historical and archaeological information on Al-Baleed dates between 1000 and 1500 CE (Medieval period). Though presently the lagoons surrounding Al-Baleed

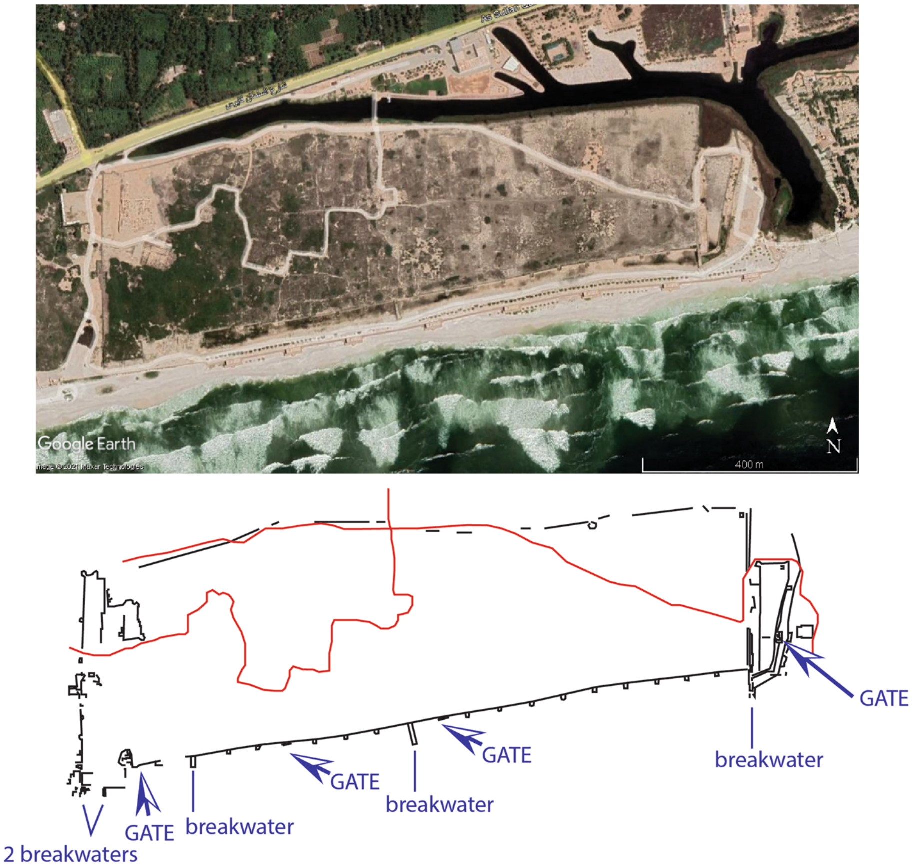

Fig. 4 Close-up and site plan of Al-Baleed (produced on Adobe Illustrator based on Newton and Zarins 2019:78, Fig. 5.4)

are largely dry, the settlement was probably an island during the years of its occupation (Costa 1979; Hoorns and Cremaschi 2004:25) with both the lagoons east and west fed with freshwater by the wadis originating from the Dhofar Mountains. The material remains of the site were visible at least as early as the mid-nineteenth century (Carter 1846), while excavations from the 1950s onward have exposed a remarkable array of structures (citadel, mosque, city wall) and associated activities. Though at the heart of the land of frankincense, historical and archaeological evidence from Al-Baleed also attests to its key role in horse trade from the Arabian Peninsula to as far as China (Newton and Zarins 2014:270).

Excavations on Al-Baleed's seaside (2009–2012) revealed seventeen towers attached to a massive city wall, as well as four monumental gates and four breakwaters. The city wall, the initial construction of which dates to the first half of the tenth century CE, was of monumental proportions with an estimated length of about 1.3 km, built in local limestone (Sassu et al. 2017). Subsequent structures (c. 1200 CE) were attached on either side of the wall, some of which bearing evidence of a population with a diverse ethnic background (Newton and Zarins 2014)—something already attested to in historical sources (Newton and Zarins 2019:40). Notably, archaeologists have excavated cist

Fig. 5 Wreck exposed in Al Baleed in 2013. The length of the boat is estimated at 3.5 m (photograph taken by and used with the permission of former Office of the Adviser to His Majesty the Sultan for Cultural Affairs, Oman)

burials that cut one of the breakwaters in half (Newton and Zarins 2019:103). In addition, the remains of approximately 35 individuals have been excavated outside of the city wall within the top 2 m of sand. These remains postdate 1200 CE and appear to have been laid on the sand in slab-lined tombs without associated grave goods, fully extended on their back or side (Newton and Zarins 2014:266).

The south wall of the city that is parallel to the seashore has received more limited attention relative to the rest of the structures of Al-Baleed. Nevertheless, this massive structure holds significant information on fluctuations in the relative sea level in this area. Newton and Zarins (2019:76) mention that between the last foundation and the first courses of the wall, they have observed a "clear rough plaster line", which likely indicates the location of the mean sea-level waterline in the tenth century CE. This location appears to be between 1.5 and 2 m higher than the present mean sea-level. Following the abandonment of Al-Baleed, the wall was covered with sand—at times the stratigraphic layers were thicker than 2 m—while later buildings were constructed above the western end of the wall and on that sandy layer. In addition, though the city wall and the jetties appear to be at a distance from the water, the features associated with maritime activities (mooring, landing, loading, etc.) required direct contact with the water. Some have argued that the breakwaters served the purpose of dry docking, though this has not been supported by the material record (Newton and Zarins 2019:84).

Large-cut blocks were excavated south of and adjacent to a breakwater lying above the current water line, and additional blocks were exposed by a seasonal monsoon in 2011 and are estimated to extend 50 m toward the sea, thus covered by meters of sand (Newton and Zarins 2019:84). In 2013, the remains of a shipwreck were exposed by the waves (Fig. 5) and archaeologists were able to collect ^{14}C that indicated a range of calibrated dates, including 1520–1590 CE, 1590 CE, 1630–1670 CE, 1780–1800 CE, and 1950 CE (Tom Vosmer, Personal Communication October 2021). Moreover, several excavated structures bear evidence of damage due to sea action (Newton and Zarins 2019:103), some of which have been conserved with the aim to prevent damage from rain and continuous exposure to moisture (Sassu et al. 2017:109). Rubble-filled walls (such as the seaward wall) and sand-filled features, are also exposed to more rapid decay, which is reasonable to assume that has been exacerbated by cyclones (heavy rainfall, strong wind, flooding). Overall, the archaeological components along the southern city wall of Al-Baleed attest to a complex mooring, docking, and loading system that was accommodating large boats. It also highlights a significant investment in resources to maintain a thriving international trade network that declined at around 1500 CE and was abandoned by 1700 CE.

Historical references to strong winds that were potentially cyclones date to 1286 CE, 1325 CE and 1853 CE (Newton and Zarins 2019:9). Moreover, evidence for a severe storm has been identified in cores from the lagoon in a layer interpreted as wash over of marine sand with planktonic foraminifera (Reinhardt 2000), representing an event dating to circa 1600–1700 CE. This event could be linked to the decline of the port (Newton and Zarins 2019:9). Hoorn and Cremaschi (2004:26) also pointed to evidence of a possible flood in the wadi a century later. Both studies suggest an ecological decline during the last three centuries of Al-Baleed, which likely aggravated an ongoing crisis resulting from, among other things, foreign intrusions (Portuguese, Turkish, Mamluk), the prohibition of the trade of key goods in Al-Baleed's economy (horses, incense, sardines), and the possible silting of lagoons (Zarins 2007:321).

Methodology

To identify and assess the impact of modern cyclones on the site of Al-Baleed, we compared satellite images taken before and after two cyclone events: Cyclone Mekunu (landfall Oman, 25/5/2018) and the more recent and less-studied deep depression ARB01 (formed overland, 29/5/2020). The 29–31 May 2020 cyclone affecting Dhofar, has not yet been inventoried by the NOAA, but its devastating effect has been extensively documented by news agencies.

Comparing two cyclones allows us to examine whether the detected location and nature of impacts are unique to these events or likely common to many cyclones. A range of satellites was used for this assessment (Table 1), each of which has different specifications. Criteria taken into consideration are: image availability (e.g. publicly available versus purchased), temporal resolution (e.g. revisit interval), spatial resolution (e.g. areal extent covered), and image quality (e.g. presence/absence of cloud cover). Using imagery of varying capabilities also allows assessment of which threats are detectable from a given satellite dataset. Given the coastal and low-lying nature of the study area, in this study we consider two main impacts likely to result from storms/cyclones: flooding and erosion.

The key components of this assessment are:

1. Regional-scale flood assessment using Sentinel-2. Sentinel-2's spatial resolution enables large area coverage at a relatively high revisit rate, and its wide spectral range (bands) allows application of different methods of water detection. In this case, flood detection was conducted using the Sentinel Water Index (SWI: Jiang et al. 2021), a typical spectral

Table 1 Summary of satellite data used in assessment of cyclone impacts at Al-Baleed

Satellite	Bands	Acquisition date and time (UTC)	Cyclone	Spatial resolution	Temporal resolution	Availability (Source)	Tide level (m to MSL) [measured/modelled]
Sentinel-2	13 bands (Vis, NIR, SWIR)	19/05/2018; 06:46:31	Mekunu (6 days prior)	10-60 m (band dependent)	5 day revisit	Public (Google Earth Engine)	0.4/0.21
Sentinel-2	13 bands (Vis, NIR, SWIR)	03/06/2018; 06:46:19	Mekunu (9 days after)	10-60 m (band dependent)	5 day revisit	Public (Google Earth Engine)	No Data/0.17
Sentinel-2	13 bands (Vis, NIR, SWIR)	23/05/2020; 06:46:29	ARB 01 (6 days prior)	10-60 m (band dependent)	5 day revisit	Public (Google Earth Engine)	0.67/0.41
Sentinel-2	13 bands (Vis, NIR, SWIR)	07/06/2020; 06:46:31	ARB 01 (9 days after)	10-60 m (band dependent)	5 day revisit	Public (Google Earth Engine)	0.81/0.51
PlanetScope	4 bands (Vis, NIR)	22/05/2018; 06:21:59	Mekunu (3 days prior)	3.7 m	1 day revisit	Free academic license (Planet)	−0.37/−0.4
PlanetScope	4 bands (Vis, NIR)	30/05/2018; 06:23:26	Mekunu (5 days after)	3.7 m	1 day revisit	Free academic license (Planet)	No Data/0.42
PlanetScope	4 bands (Vis, NIR)	20/05/2020; 06:34:39	ARB 01 (9 days prior)	3.7 m	1 day revisit	Free academic license (Planet)	0.38/0.18
PlanetScope	4 bands (Vis, NIR)	02/06/2020; 06:21:57	ARB 01 (3 days after)	3.7 m	1 day revisit	Free academic license (Planet)	0.21/−0.07
Worldview-2	8 band (Vis, Nir)	27/05/2020; 07:12:57	ARB 01 (2 days prior)	0.5 m (pansharpened)	1–4 days	Purchased (Maxar)	0.5/0.22
Worldview-2	8 band (Vis, Nir)	15/06/2020; 06:50:14	ARB 01 (17 days after)	0.5 m (pansharpened)	1–4 days	Purchased (Maxar)	0.31/−0.02

Two sets of tidal data are used: measured values from the Salalah tide gauge record hosted at the UHSLC Station Explorer (https://uhslc.soest.hawaii.edu/stations/?stn=114) and modelled values from a point 1 km offshore Salalah taken from the FES2014 global tidal model (Lyard et al. 2021). Both datasets are used owing to gaps in the measured record

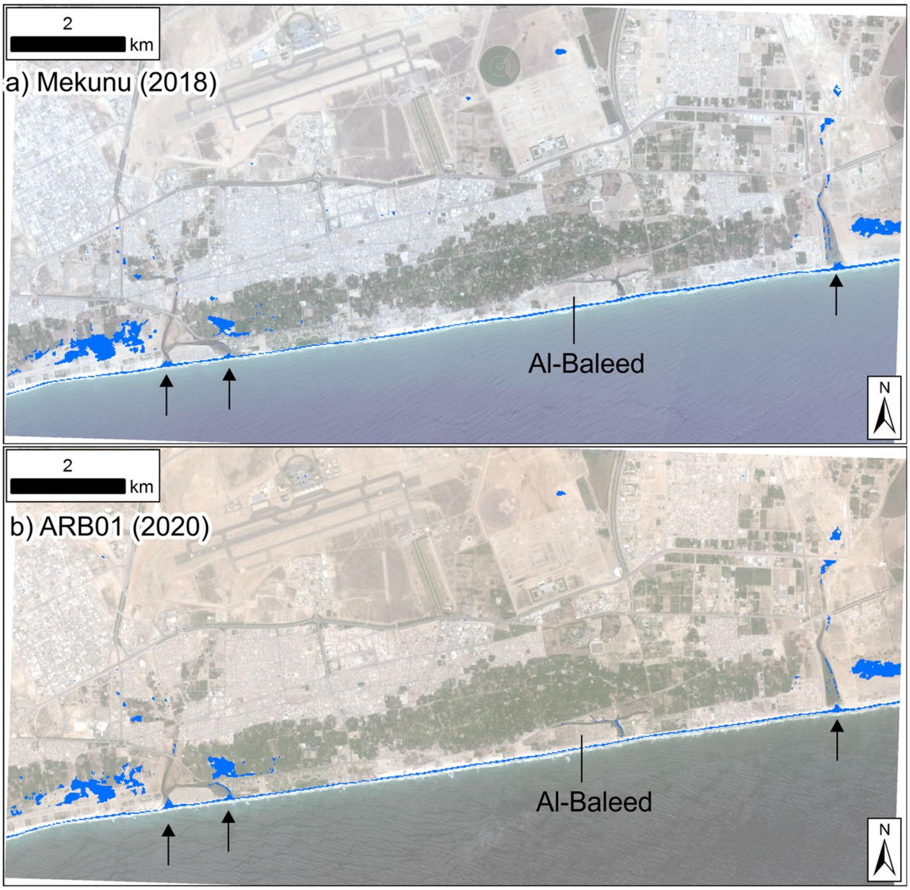

Fig. 6 Difference map of detected water from SWI assessment applied to pre- and post-event images from **a** Mekunu and **b** ARB01. Area of flood (i.e. water detected in post-event image but not in pre-event image) is shown in blue. Note the strip suggestive of coastal erosion/retreat and possible channel-mouth barrier breaches (indicated by arrows)

index which normalizes the difference between two satellite image bands, in this case Bands 5 (Vegetation Red Edge: VRE) and 11 (SWIR1), both of 20 m resolution:

$$\mathrm{SWI} = (\mathrm{VRE}-\mathrm{SWIR1})/(\mathrm{VRE}+\mathrm{SWIR1}) \tag{1}$$

Initial tests have shown that SWI provides satisfactory identification of water-covered pixels from a variety of water bodies (Jiang et al. 2021). Further, it falls within the general category of Visible-SWIR spectral indices which perform well for water detection (Boschetti et al. 2014) and which have previously been used for flood detection on archaeological sites (Tapete and Cigna 2020).

2. Site-scale flood assessment using PlanetScope images. PlanetScope lacks SWIR bands and is therefore unsuitable for application of the Vis-SWIR category of indices. Water detection was assessed using McFeeter's (1996) Normalized Difference Water Index (NDWI) which needs only green and NIR bands:

$$\mathrm{NDWI} = (\mathrm{Green} - \mathrm{NIR})/(\mathrm{Green} + \mathrm{NIR}) \tag{2}$$

Although well-established and widely used (Li et al. 2013; Zhou et al. 2017; Titolo 2021), this NDWI variant does not always identify water accurately and can struggle to distinguish surface water from other landcovers including built-up areas, wet, or dry soil (Xu et al. 2006; Boschetti et al. 2014). However, this is balanced against PlanetScope's improved spatial resolution and revisit time compared to Sentinel-2, in this case imaging Al-Baleed less than three days after each cyclone event. Very High Resolution (VHR) Worldview-2 images were also available for ARB01; however, light cloud in the pre-event image resulted in poor performance when applying water indices. Moreover, the post-event image was taken more than two weeks after the cyclone. Therefore, these images were used purely for visual assessment and cross-referencing patterns identified from the Sentinel-2 and PlanetScope imagery.

Both the regional- and site-scale flood assessments used the same basic workflow:

- Identification of clear (cloud-free) images covering the study area and bracketing the cyclone event.
- Application of water detection index (SWI or NDWI) to the satellite images.
- Thresholding the resulting water index image to separate water from non-water pixels (automated Otsu thresholding for SWI, manual thresholding for NDWI).
- Differencing the threshold of the pre- and post-event images to identify changes in water extent.

Processing for the regional-scale assessment used the cloud-based Google Earth Engine platform and its hosted collection of Sentinel-2 L1C images, while the site-scale assessment used downloaded PlanetScope imagery and ArcGIS 10.3.

3) Site-scale shoreline change assessment. Additional investigation of cyclone-driven shoreline change was conducted using the open-source CoastSat tool (Vos et al. 2019a, b). This tool takes user-selected time series of publicly accessible Landsat or Sentinel-2 imagery and automatically extracts shorelines from these images. The distance between extracted shorelines can then be measured to assess the mobility of a given beach over time. This study examined the beach fronting Al-Baleed and used a time series of 203 Sentinel-2 images from January 2016 to December 2020 inclusive. User-selectable parameters were:

Exclusion of images with poor georeferencing (failed geometric control recorded in image metadata)
Exclusion of images with > 1% cloud cover within the area of interest
Visual inspection of CoastSat outputs to exclude poorly detected shorelines

Results: Cyclone Impacts at Al-Baleed

Application of the SWI to pre- and post-event S2 images reveals the broader impact of each cyclone. Even one week after each event, large areas of standing water were still detectable 5 km east and 6–9 km west of Al-Baleed. These remain broadly consistent, with only minor variations in size for Mekunu and ARB01. Also evident is a strip of flooding along the entire coastline with increases in flood area at the mouths of at least three lagoons (Fig. 6). That this is not simply the result of a higher tide is suggested for Mekunu by similar modelled tide levels in both pre- and post-event images. For ARB01, both modelled and measured data indicate a higher tide in the post-event image, but only by < 15 cm, likely insufficient to create such a visible change along this length of coastline. The alternative is that the strip could be indicative of coastal retreat/erosion (i.e. post-event retreat resulting in landward advance of the waterline), while the larger areas could indicate breaching of channel mouth barriers. Erosion is a plausible hypothesis, as in situ visits by local partners already pointed at the actively eroding coastal scarp just south of the wall of Al-Baleed during a year not affected by a tropical cyclone (Fig. 7). Overall, the implications of the SWI assessment are that both cyclones had a similar impact in terms of areas of flooding and coastal change, but at this scale, other than the potential coastal retreat, no evidence of flooding was detectable within the intramuros area of Al-Baleed.

Visual inspection of the PlanetScope images suggested that the detected changes in beach extent were indeed genuine, particularly when tide levels are factored in (Table 1). For instance, for ARB01 there is a landward shift in the waterline despite a falling tide. For Mekunu, there is an 80 cm rise in modelled tide between pre- and post-event images which could explain the reduced beach width, but in this case the imagery also suggests disturbance to the beach itself. Not only is width reduced, but a new channel is evident on the mouth of the lagoon east of Al-Baleed, while darker areas on the beach indicate either sediment stripping down to the underlying layers or deposition of debris on the beach by waves (Fig. 8). Moreover, these images also suggest a narrow strip of flooding between the seaward boundary of Al-Baleed and the beach which occurs for both Mekunu and ARB01. This was not detected by SWI given that its width is generally < 20 m (i.e. smaller than the pixel size of the SWI input bands) and the longer post-event interval for Sentinel-2.

Fig. 7 Picture showing erosion off the coast of Al-Baleed near the pedestrian bridge in 2013 (taken by and used with the permission of Tom Vosmer)

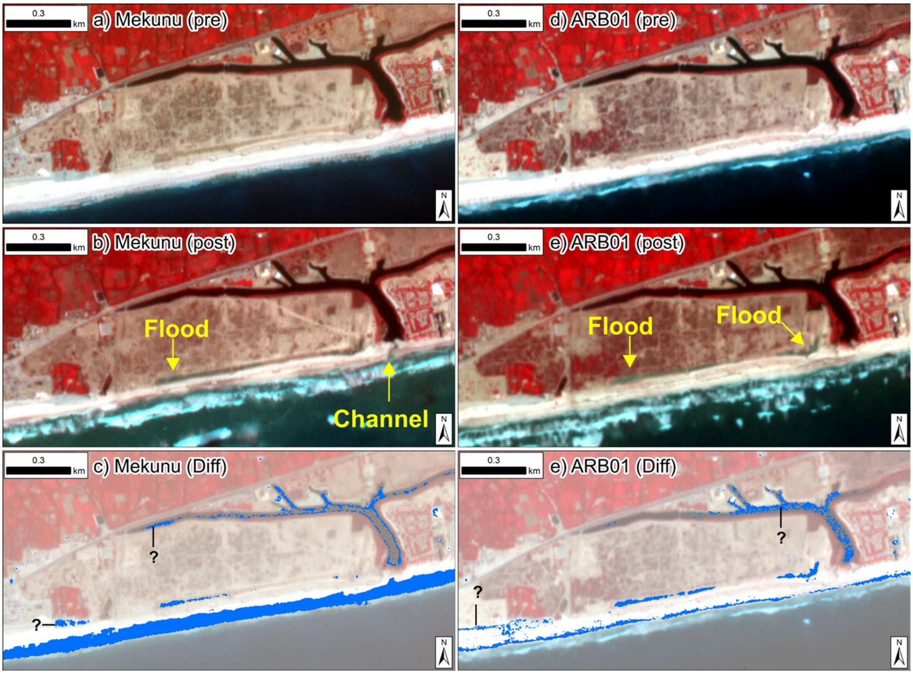

Fig. 8 PlanetScope imagery covering Al-Baleed. **a** to **c**, respectively, show pre-Mekunu, post-Mekunu, and difference map of NDWI detected water. **d** to **e** as above but for ARB01. Imagery is presented as false-colour IR composites (vegetation = red) to accentuate the appearance of flooded areas. Arrows indicate detected flooding; question marks indicate probable false water detection

Both changes (coastal retreat, flooding) were confirmed by application of NDWI and difference mapping of pre- and post-event PlanetScope images. Note however that the NDWI does have limitations, which result in false water detections west of Al-Baleed and within the surrounding lagoon, probably due to its shallow turbid nature and thus very different spectral signature compared to the open sea. However, based on both the NDWI differencing and visual comparison, the strip of flooding on the southern boundary of the site and coastal retreat appears to have had genuine impacts.

Further confirmation of coastal flooding and beach impacts comes from visual inspection of the VHR Worldview-2 images that bracket ARB01 (Fig. 9). These suggest that prior to ARB01 the area on the southern boundary of the site was not flooded, though the ground here may have been wetter. The water line (expressed by the main water mark and not the instantaneous position of the land–water boundary) was about 40–50 m seaward of the modern pedestrian bridge south of the site. After ARB01, even accounting for the two-week delay in image acquisition, the impact of flooding (possibly including residual standing water and increased precipitation) was still evident, while the main water mark had retreated to within 15–35 m of the pedestrian bridge.

Finally, assessment of a five-year time series of Sentinel-2 images using the CoastSat tool, allows the identified beach erosion to be set within the context of local coastal processes (Fig. 10). This demonstrates that both the occurrence and magnitude of identified beach erosion and coastal retreat are not exceptional. Instead, there appears to be a seasonal cycle of beach growth and retreat which broadly coincide with the monsoon season.

Fig. 9 Worldview-2 VHR images taken **a** pre- and **b** post-ARB01 and which show the flooding and coastal retreat resulting from the cyclone's impact

Nevertheless, this analysis highlights two factors with implications for endangered archaeology, which we discuss in the following section.

Discussion

First, cyclones such as Mekunu, result in very rapid loss of beach sediment in a single event of a few hours duration. This suggests that damage to archaeological remains can occur very quickly and rapidly, if they are located in areas from where this sediment is removed; for instance, remains buried under the beach. Ample archaeological evidence has been documented outside and south of the wall on and below the sand and has likely experienced both flooding and erosion (Newton and Zarins 2014:258–261). The preserved breakwaters appear to have experienced flooding, which can expose to decay structural components, such as the cut stones exposed in 2011. The flooding, erosion, and sedimentation of the area around the breakwaters, which, as mentioned in the previous sections was likely surrounded by water, bares significant information on the complex mooring and

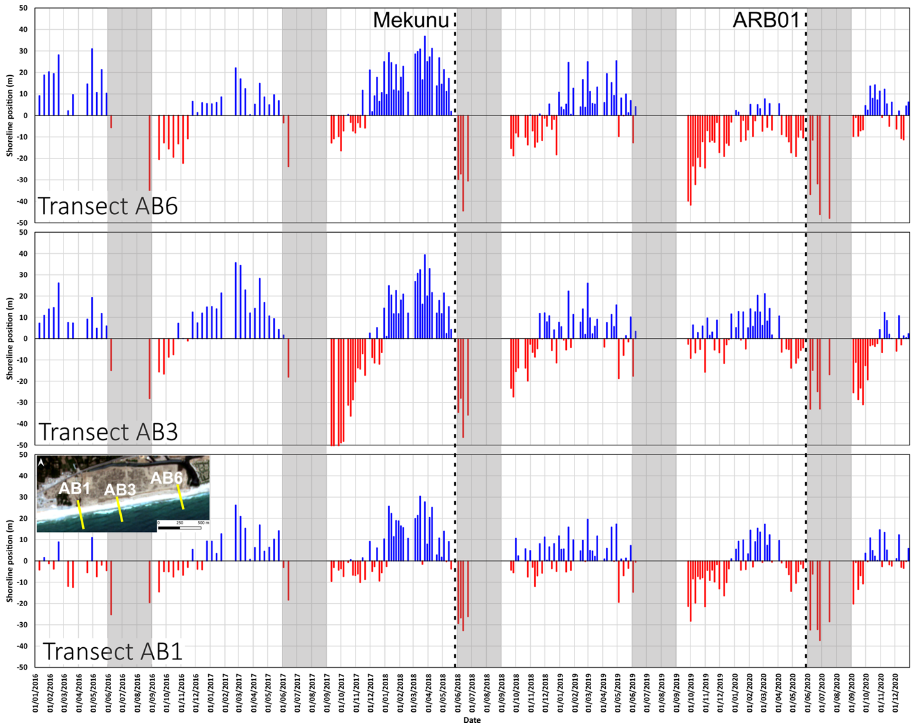

Fig. 10 Time series charts generated by CoastSat analysis of Sentinel 2 images. These give shoreline positions along selected transects across the beach of Al-Baleed (see inset map for transect location). Blue values show where shoreline distance to the transect start at a given date exceeds the average distance for all shorelines in this time interval; red shows where the shoreline distance to the transect start is less than the aforementioned average. Grey shaded areas show the generalized peak monsoon season (June–Sept); dashed lines indicate cyclones Mekunu and ARB01

docking activities taking place in Al-Baleed. The detailed understanding of those activities requires systematic excavation and could at best be disturbed by sudden exposure. Moreover, potential pieces of wood found within the breakwaters, offering invaluable information on dating and engineering (e.g. Sassu et al. 2017:108), will experience damage as a result of flooding. Likewise, the contexts of human burials on the sand are exceptionally vulnerable to flooding and erosion.

The lagoon east of the excavated area also bears valuable information on the mooring and docking activities at Al-Baleed and was associated with a gate to the city (Fig. 4) (Sassu et al. 2017:116; Newton and Zarins 2019:83). The area around the breakwater near the SE gate, for example, includes large blocks that were used to hold a dock. This area was reinforced with a protective slope. Pictures taken during this reinforcement demonstrate the existence of water even in non-cyclonic conditions (Sassu et al. 2017:116, Fig. 6). Moreover, the lagoon west of the site contains information on ancient maritime activities, including a bridge exposed in the 1970s (Costa 1979; Newton and Zarins 2019:77). Similarly, the lagoon north of the excavated area has experienced extensive disturbance by flooding. In sum, though, based on the models produced in this study, we cannot definitively identify damage to the intramuros structures, we can highlight the areas with the most disturbed contexts and these areas are at the critical intersection of land and water when this maritime site was active.

Second, our analysis suggests that beach recovery has been more limited since 2019 for all transects, and transects AB6 and AB1 also show longer intervals of reduced beach when compared to pre-2019 (Fig. 10). Possible reasons for this could include the increasing frequency of recent storms and cyclones, a reduction in sediment supply caused by human activities (e.g. upstream damming: see Hzami et al. 2021 for examples from North Africa), or a combination of the two. It is presently unclear if this represents the start of a trend or is an isolated occurrence. If it is a genuine trend, this has major implications for the preservation of Al-Baleed in the long-term. The inability of the beach to recover means that the archaeological site would lose its protection against wave erosion and would also likely suffer greater flooding during cyclones. Importantly, this will be exacerbated by twenty-first-century sea-level rise. Modelling of the Dhofar coast by Al Ruheili and Radke (2020) demonstrates how storm-driven flooding will increase considerably in this area under scenarios of 0.5–1.4 m SLR. Similarly, global-scale models of coastal retreats by Vousdoukas et al. (2020) suggest this area will experience 52–58 m of retreat by 2050 and 130–168 m by 2100 as a result of SLR. Given that the beach is 70–100 m wide under calm conditions, this suggests potential encroachment on the site by 2050 (or earlier in the case of a major cyclone event), and the active destruction of its seaward portions by 2100.

Discussion: Dealing with Loss

The inevitable loss of heritage due to tropical cyclones and climate change in general appears more drastic and rapid than ever. Considering that the impact of tropical cyclones is unlikely to be prevented (Evan and Camargo 2011), in conjunction with increasing rates of damage and destruction on MCH, as well as limited funds for research on and development of sustainable protective measures, it is useful to emphasize how to effectively manage vulnerable MCH. Banan-Dallalian et al. (2021:151) suggested that mangroves are a natural way of protecting the coastline from flooding, particularly during cyclones. Due to their strong structures, mangroves not only survive extreme environmental events, but are also found to contribute effectively to wave reduction and soil stabilization (thus preventing erosion) (Liu et al. 2013). Though mangroves can prevent the impact of waves on vulnerable coastlines, they cannot prevent flooding resulting from increased precipitation, which is common during tropical cyclones.

A common management solution applied across different international projects, including MarEA, is the production of large-scale datasets in conjunction with geographic information software (Andreou et al. 2022), which can be used to produce spatial risk models. These will inform heritage policies at a national level to prioritize action and allocation of resources, in order to reduce the consequences of tropical cyclones. Such outputs can also inform strategic planning for managing disaster. Policies, for example, could involve regular monitoring, and photographic or cloud documentation of archaeological features, which would involve significant amounts of data storage and management (and associated personnel).

Another approach viewed as one of the pathways toward the protection of MCH, would be the inclusion of cultural heritage in marine hazard mitigation and management policies (e.g. Mansour et al. 2021), and recommended (Al-Awadhi et al. 2019; Hereher 2020) national policy frameworks that will aim toward more resilient and sustainable cities in the face of the impacts of climate change. To be able to make a case for the inclusion of MCH, it is important to enhance an existing national inventory with information on the location and types of heritage, as well as associated disturbances, damages, and threats. The increasing integration of geospatial technologies in the archaeology of the MENA region (Lawrence et al. 2020), including the documentation and regular assessment of sites, has offered unprecedented opportunities for accumulating baseline information and developing informed monitoring strategies for vulnerable maritime cultural heritage (Andreou et al. 2020; Westley et al. 2021). Likewise, the integration of natural and cultural heritage within marine protected areas, e.g. the Jabal Samhan Nature Reserve in Dhofar, or the Ras-al Hadd Nature Reserve that contains important and vulnerable maritime archaeological sites, offers important opportunities for the regular monitoring of MCH (e.g. Breen et al. 2021).

In the context of Oman, Al-Awadhi et al. (2019) have argued that capacity building and improved planning are key components for the development of a national policy framework on resilience and climate change adaptation. They also identified the need for the enhancement of an existing priority list of locales that require closer attention. We consider that Oman's MCH could benefit from similar approaches that could be integrated in future resilience and adaptation plans.

Moreover, despite the lack of tidal data records before 1998 and despite limited historical information on pre-1975 cyclones (e.g. Bailey 1988), geology and archaeology offer significant opportunities for an in-depth understanding of the historical frequency and intensity of cyclones, as well as their associated impact on ancient societies and their material remains. The detection of evidence of tropical cyclones on tree rings (e.g. Slotta et al. 2019; Collins-Key and Altman 2021) presents significant opportunities for creating a long-term precipitation record for Oman, should suitable tree species be identified and sampled. Suitable wood samples excavated in Al-Baleed have been used for dating and other analyses (e.g. Belfioretti and Vosmer 2010; Ghidoni 2021), though the origin of the species can be unclear in such international contexts. Similarly, studies of the isotopic signatures of groundwater (Müller et al. 2020) and freshwater molluscs (Lawrence 1998) have contributed to the palaeoclimatic dataset that largely depends on data from caves (Burns et al. 1998, 2001; Fleitmann et al. 2004).

Finally, recent discussions on critical heritage encourage us to examine heritage in conjunction with contemporary socio-political and environmental phenomena. Among these issues, climate change, environmental sustainability, and resilience are at the forefront of discussions on cultural heritage (Meskell 2012; Harrisson 2015). In this context, it is important to examine, analyze, and quantify the impact of tropical cyclones on cultural heritage (e.g. inventorying in databases) and encourage the inclusion of this parameter in decision making. It is equally important to acknowledge damage and destruction as part of the biography of cultural heritage and identify avenues for its sustainable recording and cultural transmission, through increasingly available methods of documentation such as UAV photography, terrestrial laser scanning, and 3D photogrammetry, as well as more active incorporation of local communities in the documentation of destruction (see e.g. Ballard et al. 2020).

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