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ABSTRACT

Undocumented historical losses of sea turtle nesting beaches worldwide could overestimate the successes of conservation measures and misrepresent the actual status of the sea turtle population. In addition, the suitability of many sea turtle nesting sites continues to decline even without in-depth scientific studies of the extent of losses and impacts to the population. In this study, multidecadal changes in the outlines and area of Jana and Karan islands, major sea turtle nesting sites in the Arabian Gulf, were compared using available Kodak aerographic images, USGS EROS Declassified satellite imagery, and ESRI satellite images. A decrease of 5.1% and 1.7% of the area of Jana and Karan islands, respectively, were observed between 1965 and 2017. This translated to 14,146 m^2 of beach loss at Jana Is. and 16,376 m^2 of beach loss at Karan Is. There was an increase of island extent for Karan Is. from 1965 to 1968 by 9098 m^2 but comparing 2017 with 1968, Karan Is. lost as much as 25,474 m^2 or 2.6% of the island extent in 1968. The decrease in island aerial extent was attributed to loss of beach sand. The southern tips of the island lost the most significant amount of sand. There was also thinning of beach sand along the middle and northern sections that exposed the rock outcrops underneath the beach. The process of beach changes of both islands was tracked by the satellite imagery from Landsat 1,3,5,7 and Sentinel-2 during 1972 to 2020. Other factors including the distribution of beach slope, sea level changes, as well as wind & current from both northward and eastward components were analyzed to show its impact on the beach changes. The loss of beach sand could potentially impact the quality and availability of nesting beach for sea turtles utilizing the islands as main nesting grounds. Drivers of beach loss at the offshore islands are discussed in the context of sea level rise, dust storms, extreme wave heights and island desertification.

1. Introduction

Nesting beaches for sea turtles around the world are facing major beach erosion. Historic nesting beaches of hawksbill and green sea turtles have been reduced and impacted by humans with the remaining beach areas facing risks of further loss (McClenachan et al., 2006; Seminoff et al., 2015). Reduction of suitable nesting beaches could negatively impact the stability of sea turtle population. Four of the six offshore islands in the Saudi waters of the Arabian Gulf host the largest aggregation of nesting hawksbill and green sea turtles in the Gulf

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(Gasperetti et al., 1993; Miller, 2011a; Pilcher, 1999, 2000). Around 1000 green sea turtles and 500 hawksbill turtles nest annually at these offshore islands (Miller, 1989; Al Merghani et al., 2000; Pilcher, 1999, 2000; Pilcher et al., 2015). Of these four islands, Jana Is. is primarily used by hawksbill turtles while Karan Is. by green sea turtles with few individuals of each species using both islands (Miller, 2011a). So far, no studies have been done to assess the status of the nesting beach at the islands in particular on the aspect of beach erosion.

Coastal erosion, in general, is defined as the wasting of land along the shoreline due to a combination of natural and/or anthropogenic causes including wave action, wave and tidal currents, high winds, increasing frequency of storms and cyclones, earthquakes, landslides, dam construction, urbanization pressure, and rising sea levels (Nikolakopoulos et al., 2019; Nicholls and Klein, 2005; Brock et al., 2009). Sea level rise due to global warming has already resulted in severe coastal erosions in the 20th century and is expected to aggravate in the 21st century (Zhang et al., 2004).

Coastal erosion leads to loss of suitable nesting area for sea turtles (Schlacher et al., 2008; Hawkes et al., 2009; Kuleli et al., 2011; McClenachan et al., 2006; Reece et al., 2013; Fujisaki et al., 2018). The availability of suitable nesting beaches is predicted to be reduced particularly on low lying coastlines and small islands as a result of rising sea levels (Fish et al., 2005, 2008). Enhanced frequency and intensity of hurricanes were also reported to increase nesting beach loss and decrease hatching and emergence success (Fuentes et al., 2011; Poloczanska et al., 2009; Hawkes et al., 2009; Fujisaki et al., 2018).

The stability of sea turtle population is highly dependent on the availability of suitable nesting beach that promotes high hatching and emergence success (Zarate et al., 2003). Sea turtles depend on suitable terrestrial nesting beaches since they have an oviparous reproductive strategy (Miller, 1997; Pritchard, 1997). They are known to exhibit high fidelity to nesting beach that provide conducive environment for egg development (Carr, 1986; Miller, 1997; Ackerman, 1997; Miller et al., 2003; Brock et al., 2009). When more hatchlings emerge from the nesting beach, there is a higher probability of more individuals growing into juvenile stage and recruiting into the adult population. Upon reaching reproductive maturity, adult turtles are known to return to the nesting region where they were hatched with repeated nesting within the vicinity of the previous nests (Miller et al., 2003).

The nesting beaches at the offshore islands of Saudi Arabia are exposed to extreme climatic conditions (Miller, 2011a) such as highly elevated summer temperatures (Pal and Eltahir, 2016), very low precipitation (Almazroui et al., 2012), and strong seasonal winds (Al Senafi and Anis, 2015). These climatic conditions could affect the characteristics of the nesting beach resulting in dry sand with low moisture content, high temperature, elevated salinity, seawater inundation, and beach erosion. In particular, the nesting season of green turtles coincides with the peak of summer temperatures (Miller, 2011a). These conditions have the potential to reduce the hatching success of sea turtle nests in the Arabian Gulf.

Possible long-term beach loss at the major sea turtle nesting sites in the Arabian Gulf could exacerbate the synergistic negative impacts of extreme climatic conditions on sea turtle eggs during the nesting season. Thus, we studied the multidecadal dimension of the outlines and the extent of Jana and Karan islands by using available aerographic and satellite images to assess the long-term beach loss of the islands.

2. Materials and methods

2.1. Description of study sites

The two largest islands in the Saudi Arabian portion of the northern Arabian/Persian Gulf (hereafter called the Gulf) are Jana Is. (27°22′6.85″N, 49°53′50.85″E) and Karan Is. (27°43′5.05″N, 49°49′28.91″E). They are located approximately 46 and 80 km (respectively) offshore from the Jubail fishing port and ~ 40 km from each other (Basson et al., 1977). Although similar in most respects, Karan Is. (dimensions: 2024 m × 632 m; circumference: 5.3 km) is approximately twice the size of Jana Is. (dimensions: 1105 m × 300 m; circumference: 2.6 km) (Miller, 2011b). Both islands are situated close to the southern margin of their shallow reef flats. The primary axis of both islands extends in a northeast/southwest direction. The islands are low and flat and supported by two spines of underlying beach rock. On the northwestern side of each island is an extensive, exposed beach rock and a storm berm where flotsam and jetsam accumulate. Neither island has fresh water.

Coral sand soils were derived from the reefs and have been augmented by vegetation debris and bird guano (Basyoni, 1999). The middle parts of both islands have dense vegetation covered by low shrubs (*Suaeda* sp., *Salsola* sp.). However, turtle nesting keeps the outer margin of both islands free of vegetation (Miller, 1989).

The Gulf experiences little rainfall, most in the winter (Almazroui, 2011; Al Senafi and Anis, 2015; Hasanean and Almazroui, 2015). It receives little fresh water input because there are only few rivers that enter the Gulf (Al-Yamani et al., 2007). The high rate of evaporative water loss accounts for the relatively high concentration of salts and other ions (Michael Reynolds, 1993).

2.2. Selection of satellite images

Satellite images of Jana and Karan islands, which were provided by ESRI Satellite (ArcGIS/World_Imagery – https://qms.nextgis.com/geoservices/1300/) and accessible through the QGIS Quickmap Services Plugin, were used to analyze the island dimensions for year 2017 (Table 1, Fig. 1). The available ESRI satellite images were updated on June 29, 2017. Available Kodak aerographic images of Jana and Karan islands were used for 1965 (Miller, 2011b). The Kodak raster images with RGB bands were taken in October 1965 with corresponding map scale of 1:6000 for Jana Is. and 1:10,000 for Karan Is. The US Geological Survey (USGS) Earth Resources Observation and Science Center (EROS) released Declassified Satellite Imagery in 1995 and made it available through the USGS Earth Explorer website (USGS EROS, 1995a, 1995b). Two declassified satellite raster images belonging under Declass-1 category were available for Jana Is. (DS1104-1057DF008) and Karan Is. (DS1104-1057DF005). The two satellite images had negative polarity, 8-bit single band, and were acquired on August 11, 1968.

The Landsat series imagery (Landsat 1, 3, 5, 7) and Sentinel 2 were collected to study the quantitative evolution of beach changes of both islands during the period from 1972 to 2020 (Table 2). The calibrated top-of-atmosphere (TOA) reflectance Tier 1 products of Landsat 5,7 and Sentinel 2 images were systematically selected concerning their image quality and water levels that the images with similar mean sea level (MSL) were selected for comparison since the tidal levels can significantly alter the classification results of coastline habitat (Li et al., 2019). The images were processed using a Google Earth Engine-enabled Python toolkit, CoastSat (Vos et al., 2019), to obtain time-series of shoreline position through pre-processing (cloudy pixel removal) and Neural Network classifier. The bands used for the coastline classification algorithm were blue, green, red, near infrared, one shortwave infrared and quality assessment (BQA). Meanwhile, for the Landsat 1 (1972) and Landsat 3 (1979), only Tier 2 scaled, calibrated at-sensor radiance DN values product are available with lower resolution (60 m) in green, red and near infrared band. Therefore, Landsat 1 and 3 images were included to show only general qualitative shape of the coastline using the Canny edge detection algorithm (Canny, 1986). In addition, the beach slopes of the islands were also calculated from the ALOS World 3D – 30 m (AW3D30) dataset (Tadono et al., 2014; Takaku et al., 2014). AW3D30 is a global digital surface model (DSM) dataset acquired by the Advanced Land Observing Satellite "DAICHI" (ALOS) operating from 2006 to 2011, with a horizontal resolution of approximately 30 m (1 arcsec mesh).

Table 1
List of the satellite and aerial images used to assess the beach loss in the study.

Date	Data type	Island	Image	No. of GCPs	Source	Spatial resolution	Reference system
29/06/ 2017	ESRI Satellite imagery	Jana Is., Karan Is.		NA	ESRI ArcGIS		CRS: 3857
11/08/ 1968	Declassified satellite imagery	Jana Is.	DS1104-1057DF008	8	USGS EROS, 1995	Stereo High	No reference system
11/08/ 1968	Declassified satellite imagery	Karan Is.	DS1104-1057DF005	22	USGS EROS, 1995	Stereo High	No reference system
October 1965	Kodak Aerographic Safety Film	Jana Is.		15	Miller (2011b)	1:6000	No reference system
October 1965	Kodak Aerographic Safety Film	Karan Is.		8	Miller (2011b)	1:10000	No reference system

*GCPs – ground control points.

2.3. Georectification of the island images

The 1965 RGB satellite images were first converted to 8-bit single band using ImageJ software (Schneider et al., 2012). Then, the 8-bit single band satellite images for 1965 and 1968 were georectified using the QGIS Raster Georeferencer tool with Polynomial 1 transformation type and Cubic resampling method (QGIS, 2016). The 2017 ESRI satellite imagery was used to establish Ground Control Points of structures that were visible in the 1965 and 1968 satellite images.

2.4. Digitization of island beach boundaries

The 2017 ESRI satellite images of Jana and Karan islands were digitized manually by Google Earth View plugin in QGIS. Opening the 2017 satellite images in Google Earth View plugin allowed tracing the edges of the island at higher resolution and creating the island polygons. The island polygons were saved as (.kmz) files and were loaded into QGIS. The georectified 8-bit single band satellite images of Jana and Karan islands for the years 1965 and 1968 were examined to identify the range of pixel values to separate the water versus beach sand. Using the pixel range values, the georectified satellite raster images were classified into either sand (pixel value 1) or water and vegetation (pixel value 0) using the QGIS Raster Calculator tool. The reclassified raster images were then transformed to vector format using the QGIS Raster Polygonize tool in order to produce the polygons of the outline of the islands. The area of the island polygons was calculated using the $Area function in QGIS Attribute Field Calculator.

2.5. Measurement of beach width

The 1965 Kodak aerographic films and the June 2017 ESRI satellite images of Jana and Karan islands were further digitized to extract the boundaries of the island vegetation and calculate the width of the beach, hereby defined as the distance between the water and the vegetation line (Fig. 2). The 1968 USGS EROS satellite images were not used because of the low contrast between the sand and vegetation along the vegetation boundary lines. Transects were then digitally laid out from the vegetation line down to the seaward edge of the beach. Transects were arranged perpendicular to the vegetation line of the 2017 satellite images and were placed at 10-m interval along the beach. The orientation of transects were kept constant to detect changes in the beach width between 1965 and 2017. The length of transects were calculated using the $length function in QGIS Attribute Field Calculator.

2.6. Selection of other environmental datasets

The environmental factors including ocean currents, wind, and sea level changes, could potentially affect the coastline changes of the islands. Therefore, historical monthly wind dataset was obtained and calculated from the National Centers for Environmental Prediction (NCEP), Climate Forecast System Version 2 (CFSV2) 0.2-degree dataset, including both U and V components of the wind above the ground (Saha et al., 2011). In addition, the sea level and ocean current velocity (both U and V components) were collected from the Estimating the Circulation and Climate of the Ocean (ECCO) Version 4 release 4 (V4r4) dataset in 1° (ECCO Consortium et al., 2020a, 2020b; Forget et al., 2015). Both datasets were calculated for the period from 1992 to 2017 at the grid (49 °E, 27 °N, 50 °E, 28 °N) covering both islands.

3. Results

The land area of Jana and Karan islands in 2017 decreased relative to 1965 and 1968. A decrease of 5.1% and 1.7% of the area of Jana and Karan islands, respectively, were measured between 1965 and 2017 (Table 3, Fig. 3). This translated to 14,146 m^2 of beach loss at Jana Is. and 16,376 m^2 of beach loss at Karan Is.. There was an increase of island extent for Karan Is. from 1965 to 1968 by 9098 m^2, which could be attributed to natural dynamics of island erosion and accretion. However, comparing 2017 with 1968, Karan Is. lost as much as 25,474 m^2 or 2.6% of the island extent in 1968.

The decrease in island area extent was attributed to loss of beach sand. The southern tips of the island lost the most significant amount of sand (Fig. 4). There was also thinning of beach sand along the middle and northern sections that exposed the rock outcrops underneath the beach. The change in the shape of the islands has affected the ends more than the sides of the islands, which are stabilized by beach rock. Steep slopes were observed at the southeastern section of Jana Is. and at the southwestern section of Karan Is. (Fig. 5).

Both Jana and Karan islands showed decrease in beach width in most of the beach sections between 1965 and 2017 with the southern section showing highest beach loss (Fig. 6). Beach width reduction by as much as 253 m and 110 m were observed for Karan Is. and Jana Is., respectively. It can also be noted that sediment accretion was also observed along the western side of the southern beach section, which could probably be attributed to the long-term deposition of sand eroded from other sections of the island.

Fig. 7 shows the beach coastline changes for both islands, including the detected island edges from 1972 (Landsat 1) and 1979 (Landsat 3) images, as well as coastlines identified by the CoastSat classifier and the time series of change in distances for typical locations of each island during 1984 to 2020. The southern tips of both islands in 1972 had the similar patterns as they were found in 1965 and 1968 (Fig. 1). For Jana Is., the most apparent changes were observed in Location 1 and Location 5: Location 1 had stable coastline until its significant extension in 2015, while Location 5 had an unusual extended coastline in 2005. For Karan Is., the most apparent changes were observed in Location 1, Location 3 and Location 5: Location 1 had consistently extended its coastline since 2005, while coastline in Location 3 shrank during the same period; Location 5 had extended its coastline from 1984 to 2000, then started to shrink since then. The patterns observed in Fig. 7 can partially be explained by the slope maps of both islands (Fig. 8) that both the northwestern (Locations 2) and southeastern (Locations 4) sides of islands have steeper slopes, which make them insensitive to the beach changes.

Fig. 9 shows the time series, as well as their 6-month moving averages, of estimated areas of each island grouped by different satellite sources. The anomaly values (Jana: higher than 300,000 or lower than 75,000; Karan: higher than 1,000,000 or lower than 720,000) were excluded from the calculation. The values estimated from Landsat 5 were slightly higher than those from Landsat 7. The areas estimated by

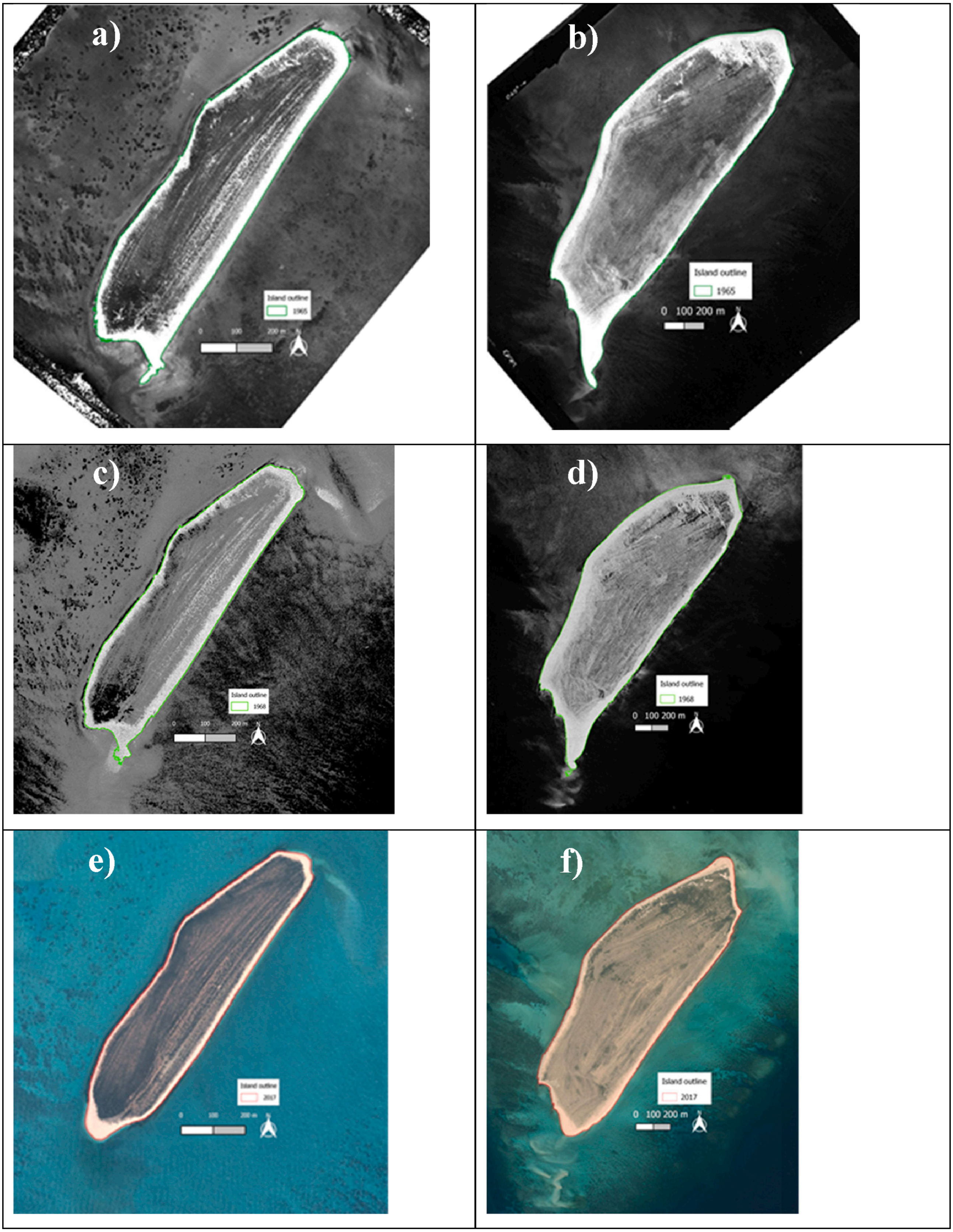

Fig. 1. October 1965 Kodak aerographic safety film (a, b), August 11, 1968 USGS EROS declassified satellite imagery (c, d), June 29, 2017 ESRI satellite images (e, f) of Jana Is. (left panels) and Karan Is. (right panels), respectively.

Table 2
List of Landsat and Sentinel-2 images used to assess the beach changes in the study.

Year	Satellite	Resolution	Jana Is.		Karan Is.	
			Date	MSL	Date	MSL
1972	Landsat 1	60 *m*	22-Sep	−0.5 *m*	22-Sep	−0.3 *m*
1979	Landsat 3	60 *m*	6-Jun	−0.1 *m*	6-Jun	−0.1 *m*
1984	Landsat 5	30 *m*	11-May	−0.2 *m*	25-Apr	0
1988	Landsat 5	30 *m*	9-Jul	0	9-Jul	−0.1 *m*
1992	Landsat 5	30 *m*	6-Sep	0.1 *m*	2-Jun	0.1 *m*
1996	Landsat 5	30 *m*	28-May	0	28-May	0
2000	Landsat 5	30 *m*	11-Aug	−0.1 *m*	26-Jul	0.2 *m*
2005	Landsat 7	30 *m*	1-Aug	−0.1 *m*	1-Aug	−0.2 *m*
2010	Landsat 7	30 *m*	14-Jul	0.1 *m*	19-Jan	−0.1 *m*
2015	Sentinel 2	10 *m*	21-Oct	0.2 *m*	21-Oct	0
2020	Sentinel 2	10 *m*	13-Mar	−0.1 *m*	13-Mar	0

the Sentinel-2 were systematically higher than both Landsat 5 & 7 and closest to the calculated values in Fig. 3. Fig. 9f demonstrates a seasonal pattern of island area change in Karan Is., yet not found in Jana Is.: more areas in spring and early summer than autumn, which can be explained by the seasonal sea level variation in Fig. 10e – sea level was highest during autumn, which decreased the beach areas. Fig. 10e also shows an increasing trend of sea water levels during 1993 to 2007. A strong coherency between ocean current and wind in both eastward and northward directions are illustrated in Fig. 10a–d, which show an increasing trend of eastward component (red squares) and a decreasing trend northward component (blue squares) during 2010–2017. However, the coastline changes of both islands cannot be clearly explained by their surrounding current and wind variations in same period.

4. Discussion

4.1. Dynamics regulating form of island and sediment deposition

Sand characteristics and distribution on Karan Is. and the surrounding reef flat are influenced by longshore currents, tidal currents that follow the axis of the Gulf and prevailing winds (Basyoni, 1999). Because of the combined processes, mobile sand cays and pits are formed at the convergence of the opposing sets of waves mainly at the southern tips of the islands. Typically, the sediments in the sand bar area are very coarse grained signaling that strong wind and shore currents transport the sediments while finer grain size materials are sorted away by the action of waves and currents (Basyoni, 1999).

The interactions between water current and surface wind in both intensity and directions are illustrated in Fig. 10, while sea level stabilized after rapid rise in 1990s. All these factors are suggested to have impact on the coastline morphology in both islands. The stronger southward wind/current would most likely be the predominant current eroding the beach sand and depositing them as temporary sand bars below the southern tips of the islands. With time, the sand bars are most likely eventually washed into the open sea.

4.2. Drivers of sediment loss at the offshore islands

Indirect impacts of climate change related events particularly sea level rise (SLR) (El-Raey, 2010; Garland, 2010; Babu et al., 2012; Hereher, 2020) and severe storm surges (El-Sabh and Murty, 1989; Neelamani et al., 2009; Lin and Emanuel, 2016) could have been operating at a slow multidecadal pace resulting in beach sediment loss at the offshore islands. The observed decrease in island area extent at Jana and Karan islands could not be directly linked to coastal developments happening at the nearby coastal zones due to their offshore distance from the mainland. In addition, sand on the beach of the offshore islands are derived from the coral reefs surrounding each island (Basyoni, 1999) and not sourced from the coastal areas.

Sea level rise results in the inundation and erosion of shorelines (Babu et al., 2012). According to the Bruun Rule, the amount of shoreline retreat in stable beaches is directly proportional to rise in sea level (Bruun, 1962; Garland, 2010; Babu et al., 2012). Sea level rise in the Gulf has been calculated over the recent decades. Alothman and Ayhan (2010) calculated a SLR of an average of 2.42 ± 0.21 mm/yr within the west of Gulf from 1980 to 2001. Using only two sea level monitoring stations in Ras Tanura and Safaniya, Sultan et al. (1995) revealed the rising sea level trend of 2.3 cm from 1980 to 1990. Hosseinibalam et al. (2007) calculated mean trend in sea level for the Gulf at about 2.34 mm/year using 10 years of data (1999–2000) from the northern Gulf stations. It is expected that the Gulf will respond to global forcing within approximately the same time frames as the global oceanic system and that by 2099, SLR in the Gulf will lie between 0.21 and 2 m (Garland, 2010). Alothman et al. (2015) predicted a relative SLR of 13 ± 3 cm by 2050. At 1-m SLR, approximately 650 km^2 of low-lying land area will be impacted along the Saudi coastline while, 2-m SLR will submerge the offshore islands of Kurayn, Jurayd, Jana, Karan, Arabiyah and Harqus (Babu et al., 2012).

Strong seasonal winds could also remove significant amount of sand from the islands. The Shamal storm system with winds blowing consistently for one up to five days from the northwest affects the whole western Gulf and could result in storm surges of about 1 m to 4 m in extreme events (El-Sabh and Murty, 1989; Garland, 2010). Shamal winds ranging from 20 to 40 knots bring some of the strongest winds during the winter and may extend into summer months of June and July with weaker winds (Perrone, 1981; El-Sabh and Murty, 1989; Hosseinibalam et al., 2007).

The offshore waters in the middle of the Gulf had an estimated 80–100 storm events per year with minimum wave height of 1.0 m, while the shallow areas towards the Saudi coast had 40–65 storm events per year based on hindcasted data from 1993 to 1994 (Neelamani et al., 2009). Extreme significant wave heights with 12-year return period between the offshore and nearshore stations around the offshore islands ranged from 2 m to 5 m with higher wave heights projected in the offshore areas (Neelamani et al., 2009).

Sand loss at the islands can also be enhanced by strong winds associated with dust storms. High wind velocities associated with dust storms can lift dust (<1–63 μm) and sand (>63 μm) from the land surface and they get transported across distances (Kutiel and Furman, 2003; Goudie and Middleton, 2006; Notaro et al., 2013; Al-Bassam et al., 2014; UNEP WMO UNCCD, 2016). The offshore islands in the Saudi waters of the Gulf are also found along the region that experienced the highest dust storms per year in the Middle East of around 10 to 60 events with associated strong winds of 15–20 m/s and above (Kutiel and Furman, 2003; Albugami et al., 2019). Data from 2000 to 2016 from the Presidency of Meteorology and Environment (PME) of Saudi Arabia shows that the annual frequency of dust storms have increased in the east and southeastern region of the Arabian Peninsula (Albugami et al., 2019).

The declining vegetation cover at the offshore islands resulting from extended periods of low-rainfall La Nina events could mean that exposed and unanchored sand on the island become more vulnerable for transport due to strong shamal winds and dust storm events (Thomas, 2011; Maneja et al., 2020). The amount of dust in the air can be reduced significantly by the presence of vegetation for a given wind velocity and/or particle size (Gillette, 1979; Kutiel and Furman, 2003). Consequently, loss of vegetation could mean loss of wind barrier function of the vegetation in the ecosystem. Wind velocities in the immediate lee of a single grass clump and a single shrub in a dryland vegetation were shown to decrease by 70% and 40%, respectively with important implications in modulating the erosivity of the wind and the erodibility of land surfaces (Mayaud et al., 2016).

4.3. Possible impacts of beach loss to the sea turtle nesting sites

The loss of sand at the islands have implications on the available

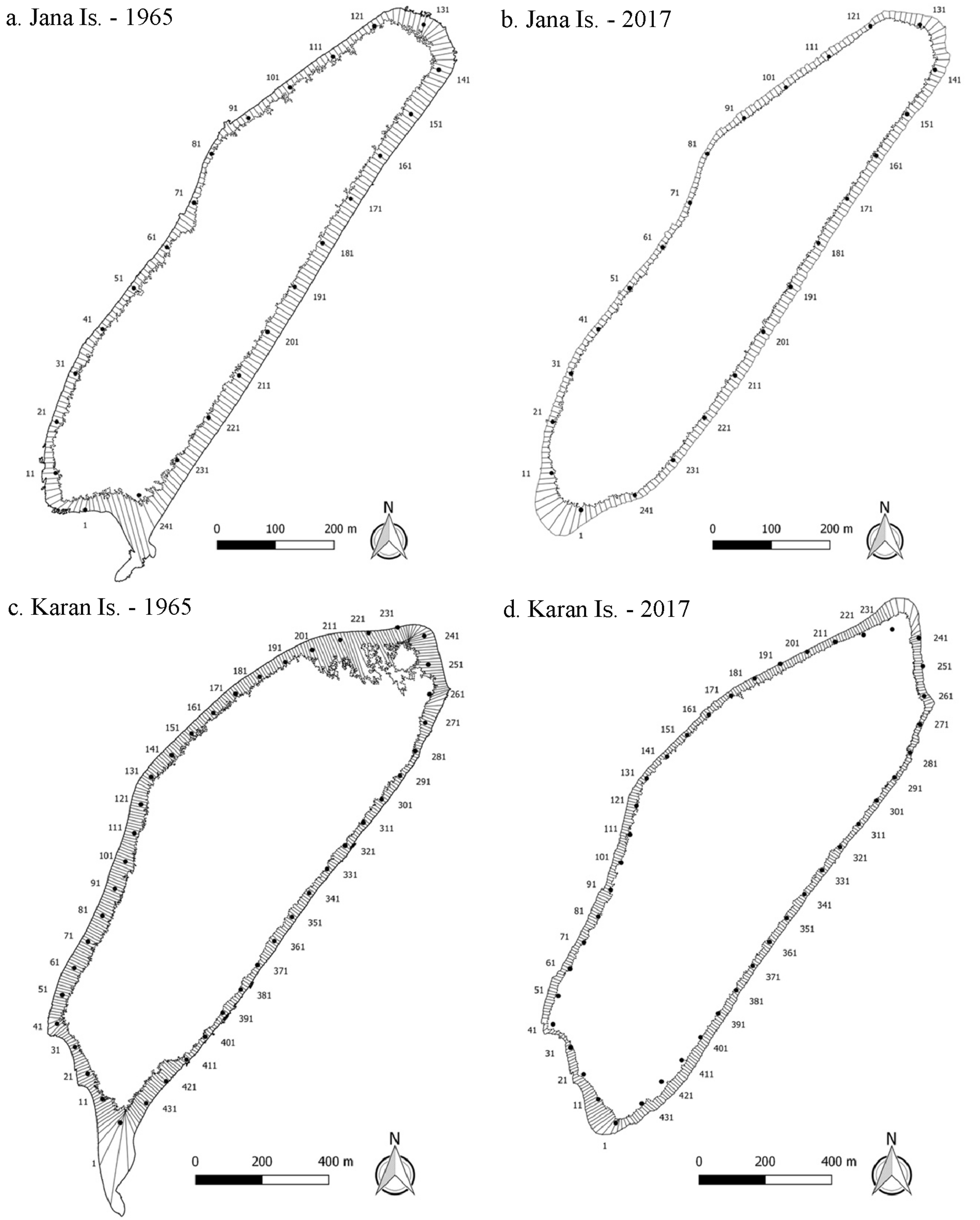

Fig. 2. 10-m interval transects for beach width measurement around Jana Is. (a, b) and Karan Is. (c, d) for 1965 and 2017. Inner dotted line – vegetation boundary. Outer solid line – island boundary. Black dots with number represent position of transects every 100 m.

Table 3
Measurements of the areal extent of Jana and Karan islands in 1965, 1968 and 2017.

Year	Area (square meters)	
	Jana Is.	Karan Is.
1965	275,231	986,349
1968	268,291	995,447
2017	261,085	969,973
Area loss (1965 vs 2017)	14,146	16,376
% Area loss (1965 vs 2017)	5.1	1.7

nesting beach suitable for successful nesting and egg development. This poses problems to sea turtle nests deposited at the islands with the aggravated impacts of salt water inundation, beach slope steepness, decrease in sediment grain size quality, and higher salinity sand for incubation (Wood and Bjorndal, 2000; Brock et al., 2009; Maison et al., 2010; Stewart et al., 2019). Although the time scale seems long, the impact of the changes in the shape of the beaches occurs during the nesting season when turtles are attempting to lay eggs and during the incubation of the eggs. A significant change in the shape of the islands can force turtles to nest closer to the vegetation line (Fujisaki et al. 2018) or among the stranded debris (Triessnig et al., 2012; Nelms et al., 2016), which can impact nesting and incubation success. The observed thinning of beach sand along the middle and northern sections of the island exposes the beach rock, which could potentially impede the access of the nesting turtles to the beach and back to the sea. In addition, the hatchling turtles could get trapped between the crevices of the beach rock when they approach the sea during low tide.

Removal of beach sand by erosion could result in steeper slopes that prevent nesting turtles from accessing the nesting site (Wood and Bjorndal, 2000; Maison et al., 2010). Alteration of nesting beach profile and slope could render it unsuitable for nesting as nesting success of loggerhead and green sea turtles have been reduced as an immediate result of beach nourishment (Brock et al., 2009); the effects of which could last for at least one season depending on the species of sea turtles.

When nesting beach areas are reduced, there is a tendency for the sea turtles to be concentrated in one area that can result in exceeding the nesting carrying capacity of the remaining beach section (Mazaris et al., 2009). The negative consequence of exceeding the carrying capacity is that density-dependent mortality is triggered since nests deposited earlier have higher chances of being disturbed and re-excavated by new nesting turtles. This action kills the eggs either by direct damage or by exposure to predators and microbes. Mazaris et al. (2009) demonstrated that beach loss triggered density-dependent mortality of eggs resulting in reduced hatchling production of loggerhead sea turtles at Sekania nesting beach in Greece. Density-dependent nest destruction was also reported using computer simulations with leatherback nesting areas in Suriname and French Guiana (40% of the world's nesting sites), where increased nesting female density led to increased intraspecific nest

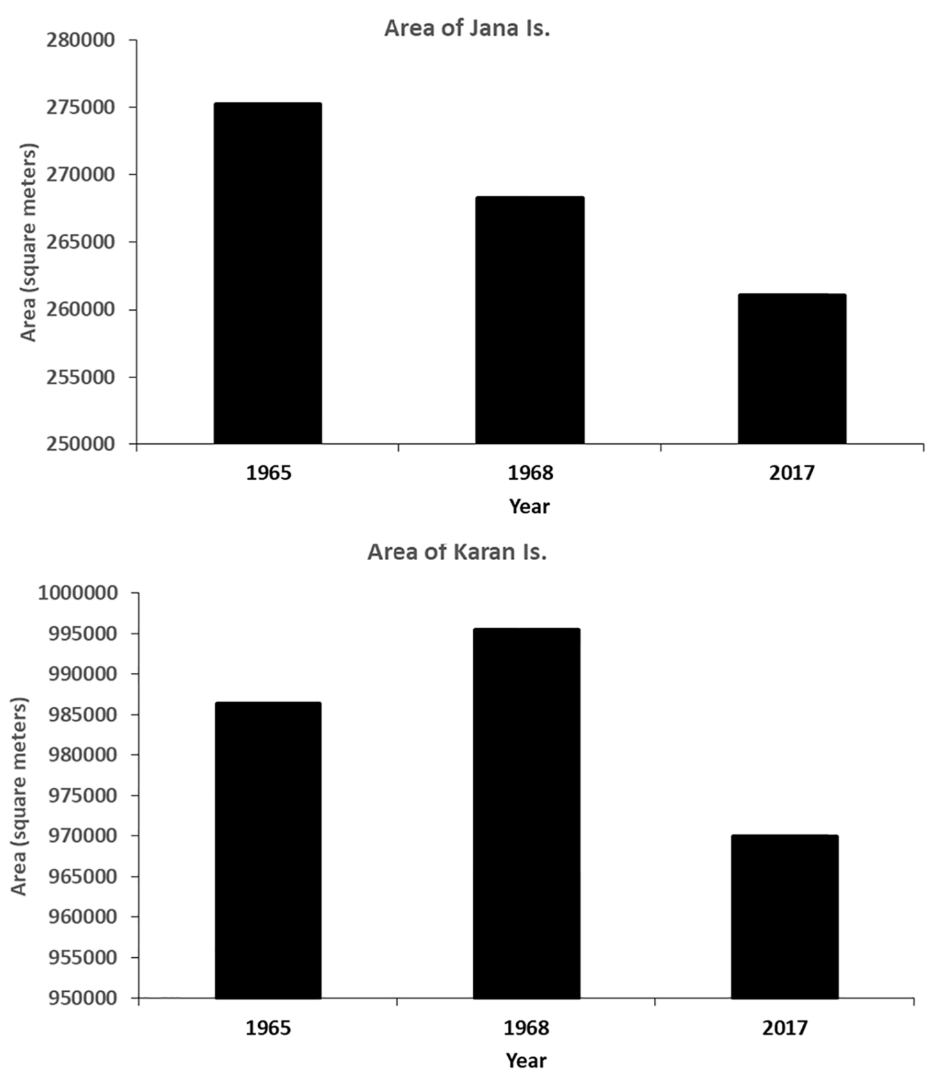

Fig. 3. Area in square meters of Jana and Karan islands measured in 1965, 1968 and 2017.

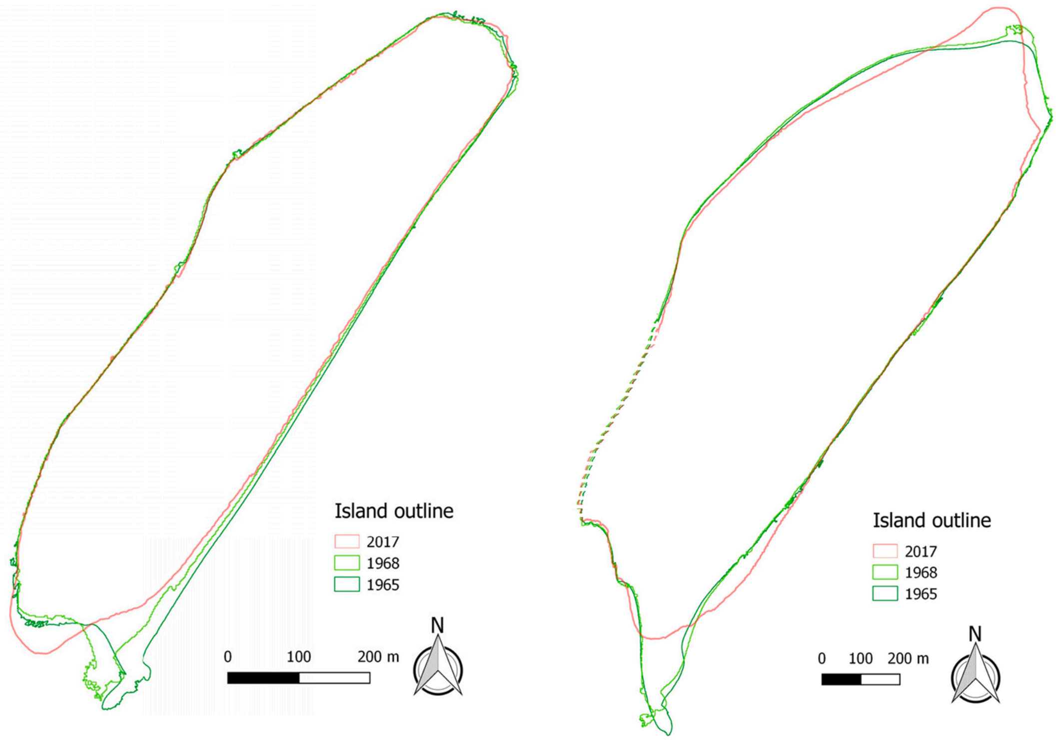

Fig. 4. Outlines of the aerial extent of Jana Is. (left panel) and Karan Is. (right panel) measured in 1965, 1968 and 2017 using aerial and satellite imagery.

Fig. 5. Sections of the beach with developed steep slopes at the southeastern section of Jana Is. (Top panel Nov 26, 2019; Middle panel May 22, 2019) and at the southwestern section of Karan Is. (Bottom panel July 11, 2019).

destruction with subsequent effect of feminization because the surviving nests laid later in the season have incubated in much warmer temperature (Girondot et al., 2002). Tiwari et al. (2006) included nest destruction by nesting females and predation by wild animals as part of the density-dependent factors affecting green turtles at Tortuguero, Costa Rica. This can become a case at Karan Is. where nesting preference is concentrated at the middle to southern beach sections (Maneja et al., 2020). In this study, major narrowing of beach areas was reported at the southern, western, and northern sections at Karan Is. Though, sea turtle nesting is evenly distributed around Jana Is. (Maneja et al., 2020), development of steep slopes along the southeastern section could prevent turtles from accessing the beach, probably pushing them to concentrate in more accessible areas of the island resulting in higher nesting density. Almost all the beach sections of Jana Is. also recorded decrease in beach width with major reductions at the southern end.

The combined effects of sediment loss and rising sea level could result in a phenomenon called “coastal squeeze” where coastal habitats are squeezed into a narrowing zone (Doody, 2013; Pontee, 2013). Reduction of beach width as a result of sediment loss means that the high tide levels could reach closer to the turtle nests that are now squeezed closer to the vegetation line. This could increase the risk of saltwater inundation of nests leading to higher egg mortality and lowering of hatching success (Foley et al., 2006; Tiwari et al., 2006; Özdemir et al., 2008; Fujisaki et al., 2018). At a rate of as much as 11 m/year of beach loss at an eroding barrier island beach in Florida, loggerhead turtle nests have been shifted and were squeezed closer towards the vegetation line (Fujisaki et al., 2018). Nesting more inland beyond the vegetation boundary line is prevented by the high compactness of sand as in the case in Jana and Karan islands. This prevents the turtle from digging the appropriate depths of the nest. Nesting tracks of turtles were observed to reverse their directions back to the sea once the hard substrate inside the vegetation area were encountered by the turtles.

Loss of habitat may also result in fewer nests deposited (Fujisaki et al., 2018). McClenachan et al. (2006) reported that 20% of historic nesting sites of hawksbill and green sea turtles have been lost in the Caribbean with 50% of the remaining nesting sites reduced to dangerously low populations due to beach loss. They warned that by not taking into account the historical nesting beach loss, current trends in population increase might overestimate the status of the species.

To date, there is no comprehensive analysis of the long-term trend of the numbers of nesting sea turtles at Jana and Karan islands. Al Merghani et al., 2000 and Miller (2011a) provided the numbers of nesting hawksbill and green sea turtles encountered at Jana and Karan islands,

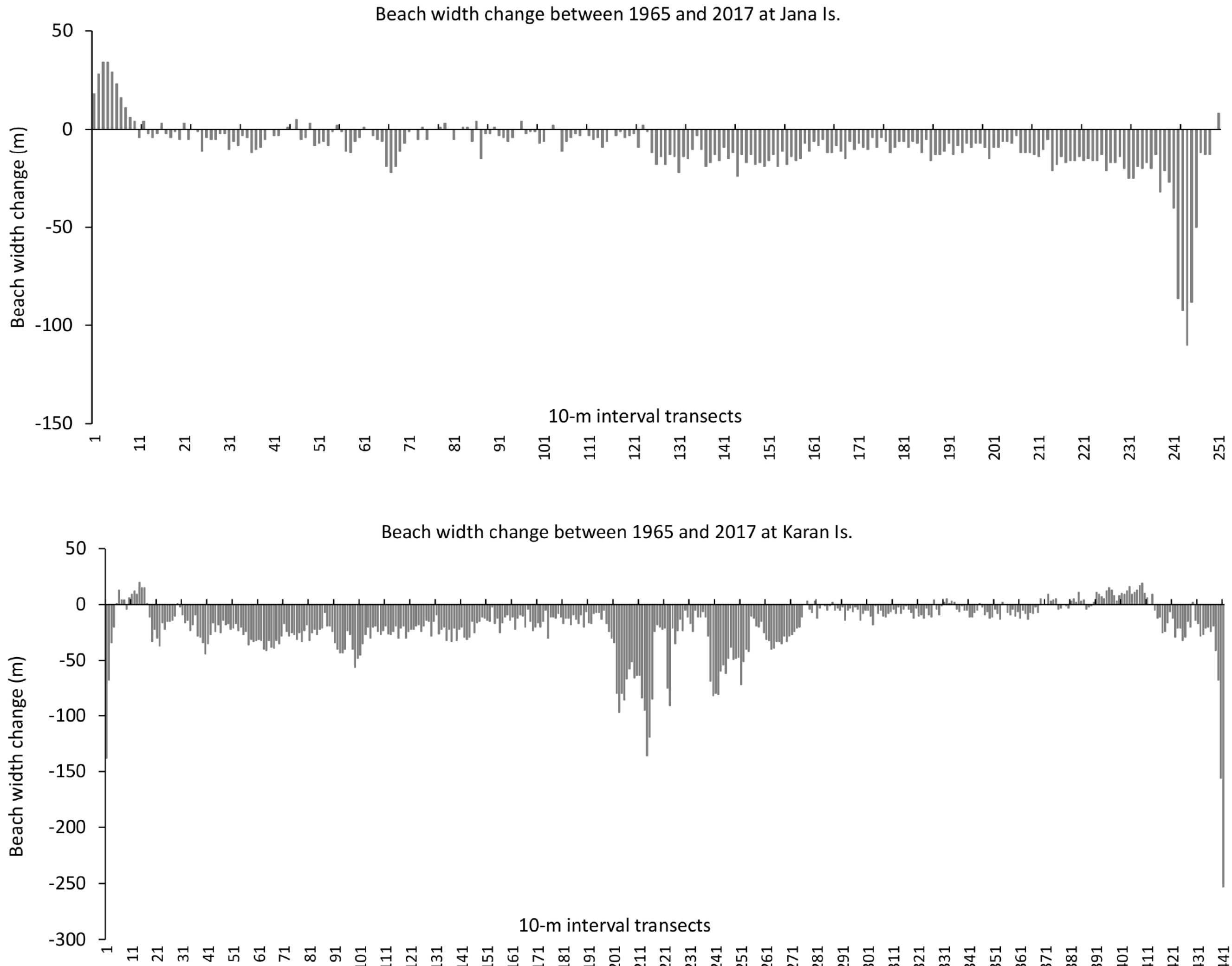

Fig. 6. Changes in beach widths along the 10-m interval transects at Jana Is. (top panel) and Karan Is. (bottom panel) between 1965 and 2017. Negative and positive values show decrease and increase in beach width, respectively.

respectively, from 1986 to 1997. However, the number of sampling days varied among the years, which prevents making an interpretation at this time. Further monitoring is warranted to determine if the number of nesting turtles has been impacted by the documented beach loss of the islands in this paper.

4.4. Natural events that enhances negative impacts of island beach loss

Synergy of extreme natural events can exaggerate the impact of beach loss on sea turtle nesting sites *vis-à-vis* the SLR phenomenon in the Gulf. Garland (2010) argued that other risks accompany the direct impact of SLR and enhance coastal erosion including higher extreme tides and waves, elevated low-pressure surges and greater wave run-up. The nesting season of sea turtles in the Saudi waters coincides with the higher mean sea level in July and August with the lower levels registered in the winter season (Sharaf El Din, 1990; Sultan et al., 1995). The difference between the seasons was 26 cm with analysis of data from 1980 to 1990 (Sultan et al., 1995). The differences in the mean sea level are significantly influenced by meteorological air pressure conditions among the seasons. In addition to atmospheric forcing, sea level in the Gulf is higher in summer and autumn than in winter and spring due to thermal expansion of warmer waters with monthly mean thermosteric height ranges from + 2.2. cm in July and −2.1 cm in February (Hosseinibalam et al., 2007). Higher mean sea levels during the nesting season could result in higher risk of seawater inundation of nests deposited closer to the water line. The decrease in beach width could squeeze the nests between the vegetation line and the high water tide. The tide system at Karan and Jana islands is dominated by mixed, mainly semi-diurnal tidal type (Siddig et al. 2019). Jana and Karan islands are located in between two tide stations in the Saudi waters namely, Abu Ali Pier and Arabiyah Island. Tidal range observed at these stations were 1.27 m and 1.60 m for Abu Ali Pier and Arabiyah Island, respectively.

Although no studies so far have focused on the linkage of SLR in the Arabian Gulf with global atmosphere–ocean interactions such as the El Niño-Southern Oscillation (ENSO), Han et al. (2010) and Alawad et al. (2019) documented the mechanism of how El Niño, the warm phase of ENSO, induces wind-driven massive transport of water from the western Pacific into the Indian Ocean and raises the sea level anomaly of the marginal basins such as the Red Sea and Gulf of Aden. Muis et al. (2018) reported significant correlations between ENSO and extreme sea levels with impacts on coastal flooding. Thus, further studies are recommended to investigate the possible influence of El Niño on the beach loss recorded at the offshore islands.

5. Conclusions

The recorded beach loss at the offshore nesting islands from 1965 to

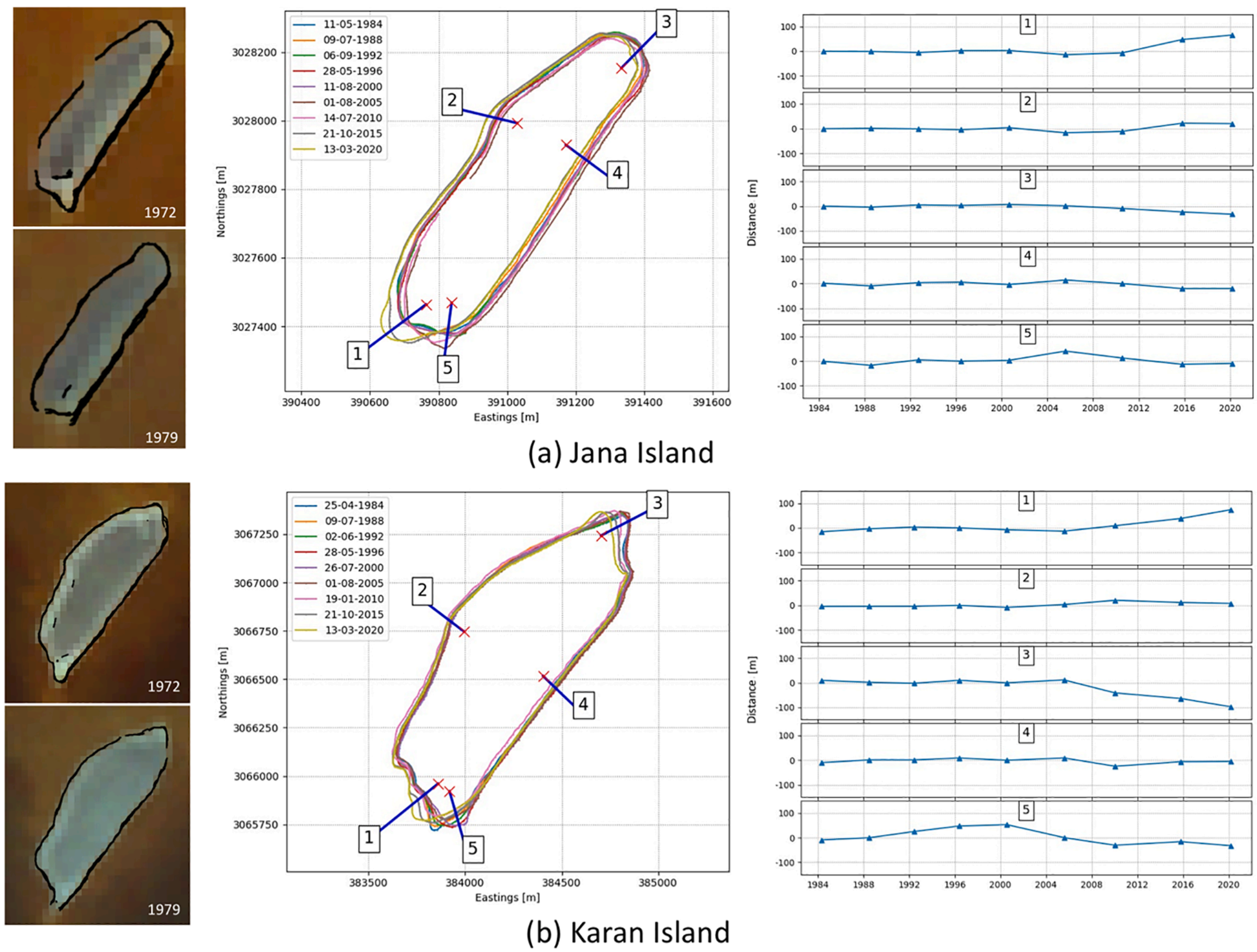

Fig. 7. The coastline changes from 1972 to 2020 in (a) Jana and (b) Karan islands from Landsat and Sentinel-2 imageries. The time series in the right column represent the distance to the original 1984 coastline in 5 typical locations of each islands, with positive/negative values representing extending/shrinking beaches, respectively.

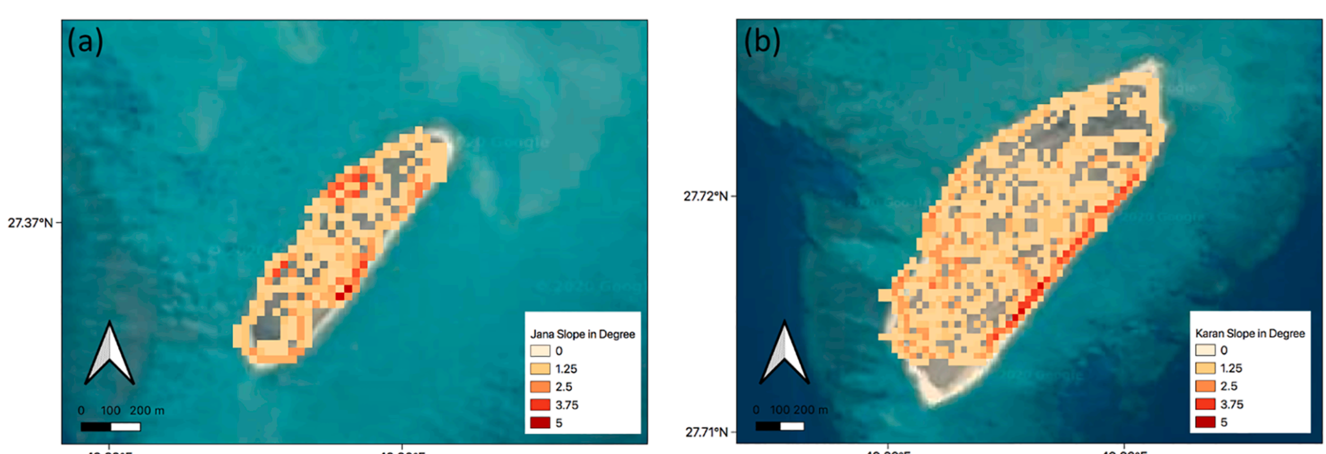

Fig. 8. The maps showing land slopes of both a) Jana and b) Karan islands.

2017 in this study revealed the degree of change in the major nesting ground of sea turtles inside the Gulf. Decreasing beach width, altered slopes and beach profile, and possible changes in the grain size composition could have significant negative implications on the long-term suitability of the islands as sea turtle nesting sites. The synergistic effects of sea level rise, more frequent and intensified dust storms, Shamal winds and extreme wave heights, and island desertification add to the factors that could exacerbate the negative impacts of beach loss on the sea turtle nesting and hatching success.

The multidecadal decline in the suitability of the nesting beach for

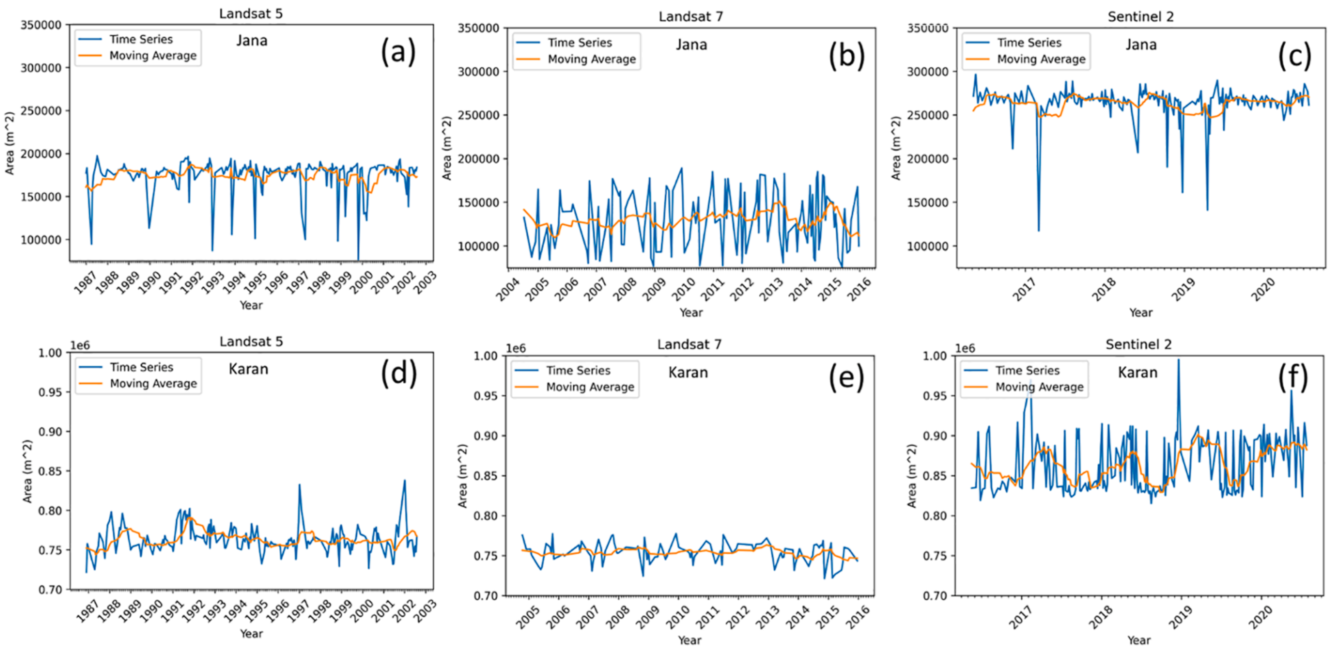

Fig. 9. Time series plots of estimated areas by satellite images for each islands grouped by the satellite sources: Landsat 5, Landsat 7 and Sentinel 2.

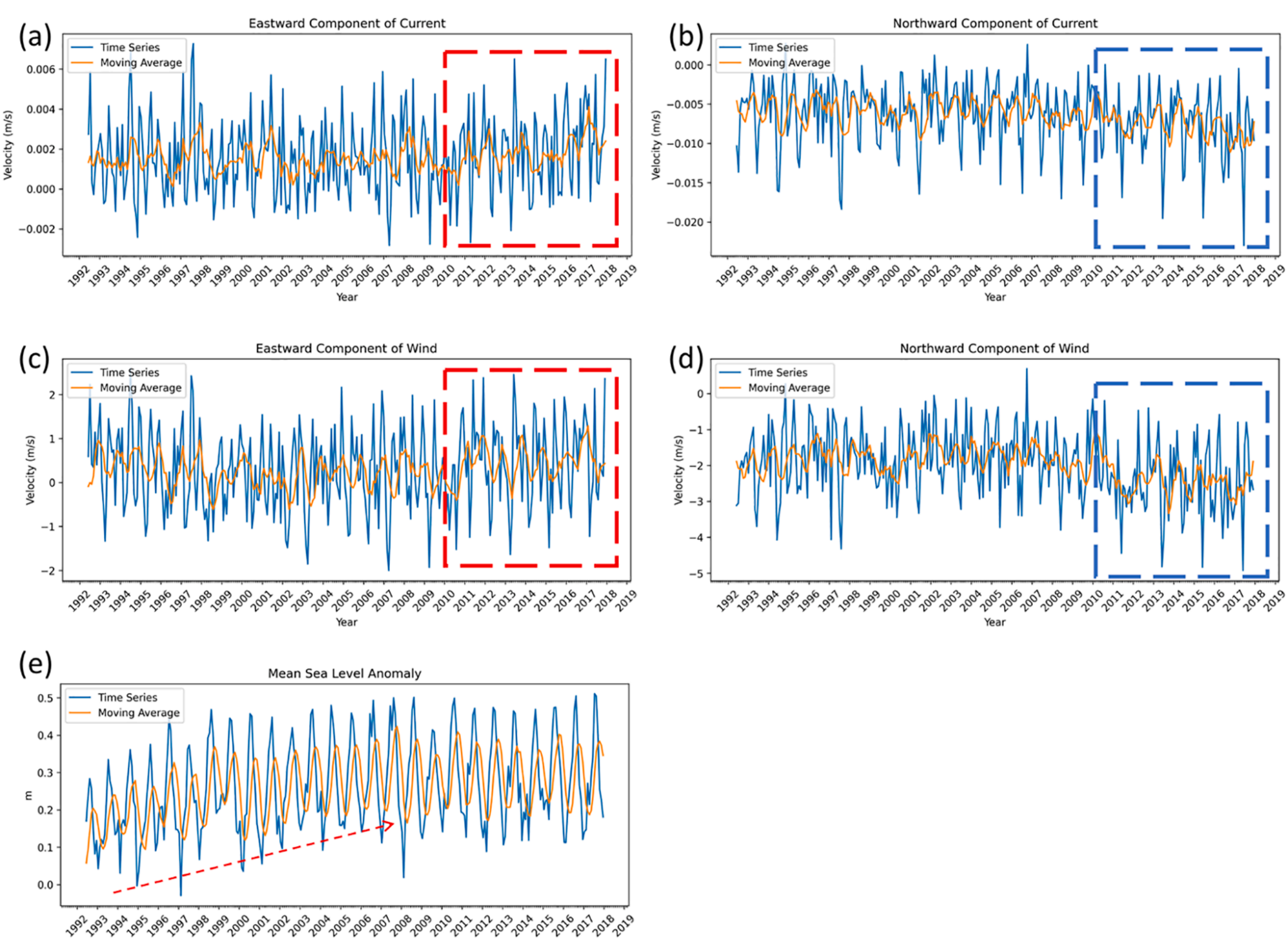

Fig. 10. The time series of eastward and northward components of current and wind, as well as mean sea level anomaly during 1992–2017 at the grid (49 °E, 27 °N, 50 °E, 28 °N) which covers both islands.

hawksbill and green sea turtles at the major offshore nesting islands of Karan and Jana may reduce the long-term stability of the sea turtle population inside the Gulf particularly. Possible reduction in hatching success will negatively affect the number of recruits to the adult turtle population. In addition, given the high fidelity of sea turtles to return to their natal origin for nesting, continued beach loss could mean more failed nesting attempts due to low suitability of sand for nesting, and occurrence of density-dependent mortalities and sex determination. The analysis of beach loss is only one of the important aspects that are required to assess the overall status and trend of sea turtle population in the Gulf. More in-depth studies are also required to assess the interaction of the sea turtle population inside the Gulf with that of the wider Distinct Population Segments of the Indian Ocean (Seminoff et al., 2015). In particular, studies must be conducted whether juveniles hatched from minor nesting sites inside the Gulf or from the other major nesting grounds in the northern Indian Ocean recruit into the foraging areas of the turtles that nest at the offshore islands of Karan and Jana. Consequently, the long-term decline in sea turtle population inside the Gulf could reduce the productivity and health of the marine habitats such as seagrass meadows and coral reefs that serve as sea turtle foraging areas.

CRediT authorship contribution statement

Rommel H. Maneja: Conceptualization, Methodology, Writing - original draft, Visualization, Investigation. **Jeffrey D. Miller:** Conceptualization, Writing - original draft, Supervision. **Wenzhao Li:** Software, Data curation, Visualization, Investigation. **Rejoice Thomas:** Software, Data curation, Visualization, Investigation. **Hesham El-Askary:** Supervision, Conceptualization, Writing - review & editing. **Sachi Perera:** Software, Data curation, Visualization, Investigation. **Ace Vincent B. Flandez:** . **Abdullajid U. Basali:** . **Joselito Francis A. Alcaria:** . **Jinoy Gopalan:** . **Surya Tiwari:** . **Mubarak Al-Jedani:** . **Perdana K. Prihartato:** . **Ronald A. Loughland:** . **Ali Qasem:** . **Mohamed A. Qurban:** . **Wail Falath:** . **Daniele Struppa:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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