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Evolutionary dynamics of island shoreline in the context of climate change: insights from extensive empirical evidence

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ABSTRACT

The evolution and future trajectory of island shorelines, amidst global climate change, are of increasing concern to governments, communities and researchers worldwide. However, the field of island studies is often hampered by a lack of data and inconsistent methodologies, leading to an inadequate understanding of the processes driving shoreline changes on islands within the context of climate change. This research aims to bridge this gap by analyzing islands in Southeast Asia, the Indian Ocean and the Mediterranean Sea from 1990 to 2020 using remote sensing. Of over 13,000 islands examined, approximately 12% experienced significant shifts in shoreline positions. The total shoreline length of these islands approaches 200,000 km, with 7.57% showing signs of landward erosion and 6.05% expanding seaward. Human activities, particularly reclamation and land filling, were identified as primary drivers of local shoreline transformations, while natural factors have a comparatively minor impact. Moreover, the ongoing rise in sea levels is identified as an exacerbating factor for coastal erosion rather than the primary cause. Drawing from these findings, we propose several adaptive measures for islands in response to climate change. Taken together, this research provides comprehensive data and a basis for decision-making for sustainable development of island territories.

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Island; shoreline change; climate change; sea level rise; adaptation

1. Introduction

Islands are unique and valuable ecosystems on Earth, characterized by abundant coral reefs, marine biodiversity, and distinctive plant species (Barajas Barbosa et al. 2023; Cámara-Leret et al. 2020). They provide habitats and breeding grounds for numerous species, serving as important stopovers and habitats for migratory birds and marine animals (Valente et al. 2020). Additionally, islands are of significant economic and cultural importance for local inhabitants (Adshead et al. 2021).

Under the escalating challenges of global climate change, island nations, especially smaller islands, are confronting significant threats, a concern that has achieved broad consensus in the scientific community (De Scally and Doberstein 2022; Kelman et al. 2019; Petzold and Magnan

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2019). The United Nations' 2030 Agenda for Sustainable Development addresses numerous goals related to the sustainable development of small island states.

As global temperatures rise, the melting of glaciers and the thermal expansion of seawater are leading to a continuous rise in sea levels, posing serious risks for low-lying island nations, including coastal erosion, flooding and saltwater intrusion into inland areas. These direct threats not only jeopardize the safety of residents and the integrity of ecosystems but also have detrimental effects on infrastructure, housing, national economies and social progress (Martyr-Koller et al. 2021; Nienhuis and Lorenzo-Trueba 2019; Tuck et al. 2019). Additionally, the increased frequency of storm surges and extreme weather events presents further risks to these nations. Climate change is associated with stronger storms and unpredictable precipitation patterns, increasing the vulnerability of coastal areas (Hossain et al. 2022b; Mondal et al. 2021). The resulting impact of tsunamis and powerful ocean waves can cause extensive destruction, while subsequent flooding threatens urban areas, agricultural lands, and critical infrastructure, as well as the safety and livelihoods of residents (Ayyad, Hajj, and Marsooli 2023; Fuhrmann, Wood, and Rodgers 2019; Houser, Wernette, and Weymer 2018).

However, the initiation of international research on island shorelines has been relatively delayed due to challenges in data collection and field surveys (Zhang et al. 2014). Current academic work primarily concentrates on a limited number of islands or atolls, with the objective of examining the spatiotemporal dynamics of island shoreline changes and deciphering the underlying driving mechanisms (Ford and Kench 2015; Nandi et al. 2016). Through a comprehensive review of existing literature and statistical analysis, the spatial distribution of the islands studied has been illustrated in Figure 1. As the investigation of island shorelines gains prominence among governments, academics, the public, and the media (Mondal et al. 2020; Thakur et al. 2021), a wide range of studies have emerged, offering varied conclusions and viewpoints.

The first perspective emphasizes the significant coastal erosion attributed to rising sea levels. This trend has been exemplified in a case study of the Hawaiian Islands, particularly Oahu and Maui (Romine and Fletcher 2013). Notably, Maui has recorded a rate of sea level rise (SLR) approximately 65% higher than that of Oahu. An in-depth analysis of coastal evolution shows that Maui has undergone the most pronounced beach erosion, with 78% of its beaches experiencing erosion, in contrast to 52% on Oahu. Upon considering additional factors such as wave dynamics, sediment availability, littoral processes and human activities, the varying rates of relative SLR around Oahu and Maui are identified as the key factors explaining the differing shoreline trends (Romine et al. 2013). Another case study from the Solomon Islands further illustrates the significant coastal

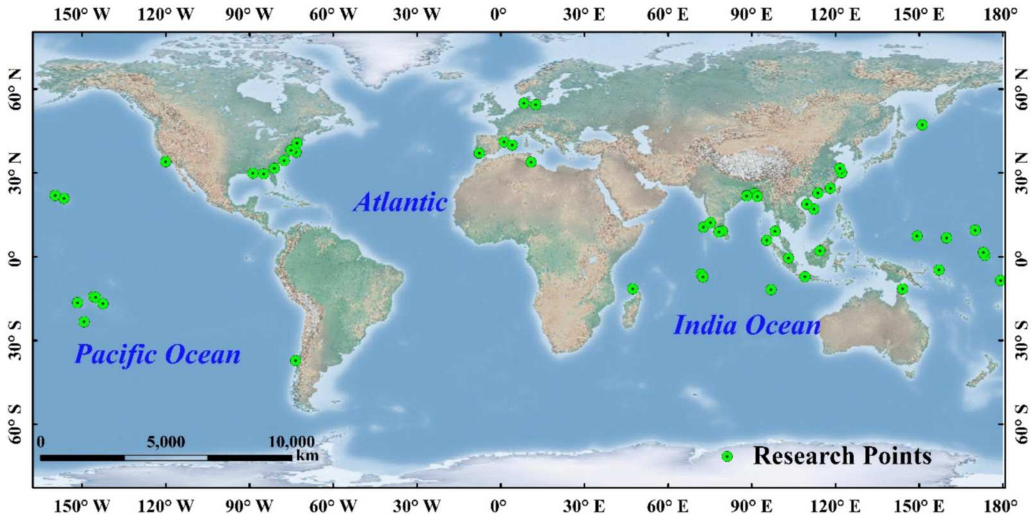


Figure 1. The spatial distribution of the investigated islands in present literature.

erosion due to rising sea levels. Analysis of time series aerial and satellite imagery from 1947 to 2014, covering 33 islands and incorporating historical accounts from local sources, revealed the complete disappearance of five vegetated reef islands during this period. Additionally, six other islands have been reported to experience severe shoreline recession (Albert et al. 2016).

The second perspective argues that, despite rising sea levels, many island shorelines have maintained relative stability or equilibrium without significant alterations. A comprehensive reexamination of data on 30 Pacific and Indian Ocean atolls, encompassing a total of 709 islands, has demonstrated that none of the atolls experienced a loss in land area. Furthermore, 88.6% of the islands were either stable or increased in size, while only 11.4% showed a decrease in area. Intriguingly, islands within atolls subjected to rapid sea-level rise did not exhibit significantly different patterns than those on other atolls (Duvat 2019), which is supported by observations from the Manihi and Manuae atolls in French Polynesia. Over the past 50 years, there have been data indicating that 47 reef islands predominantly expanded in area or remained stable despite experiencing a rate of sea-level rise that exceeds the global average (Yates et al. 2013), and similar findings have been noted in the Tetiaroa and Tupai atolls (Le Cozannet et al. 2013), as well as in the Tuamotu Archipelago (Duvat, Salvat, and Salmon 2017a) within the same region.

The third perspective suggests that despite the rising sea levels, island shorelines have not experienced erosion and have rather undergone accretion, resulting in land expansion towards the sea (Dawson and Smithers 2010; Ford 2013; Sengupta, Ford, and Kench 2021). Additionally, it is argued that large-scale human activities such as land reclamation have played a significant role in the seaward expansion of islands, eclipsing the effects of sea-level rise. This view is supported by a study of the 101 islands of Tuvalu, a Pacific reef nation, which revealed a net increase in Tuvalu's land area by 73.5 hectares (2.9%), despite the ongoing sea-level rise, with land area gains observed in eight of the nine atolls examined (Kench, Ford, and Owen 2018). Furthermore, human-induced land reclamation has been shown to cause notable expansions of island shorelines, effectively overshadowing the impacts of natural factors such as sea-level rise and wave action. For instance, a study conducted on the Zhoushan Archipelago in China, where significant seaward expansion has been observed on almost all inhabited islands over recent decades, has reported a substantial increase in areas designated for harbors, towns and industrial activities (Zhang et al. 2014), with similar trends reported in various other global locations (Chee et al. 2023; Duvat 2020; Nazeer et al. 2020; Subraelu et al. 2022).

The academic community has demonstrated considerable interest in and dedication to understanding the evolution of island shorelines in the context of climate change (Kench et al. 2023; Mouillot et al. 2020). The prevailing consensus and viewpoints in this field are scientifically robust and supported by empirical data. However, research in this field can be hampered by inconsistencies in the obtained data and methodologies and a limited scope of study. Thus, a comprehensive understanding of the spatiotemporal characteristics, patterns and driving mechanisms behind island shoreline evolution in the context of climate change and human activities remains unclear.

To address these limitations, this study utilizes a standardized dataset and a quantified methodology for examining shoreline changes since 1990 in a substantial geographical area, including the Southeast Asian archipelagos, the Indian Ocean and the Mediterranean islands, collectively covering more than 13,000 islands, with the primary objective to provide robust evidence on the long-term evolutionary characteristics and trends of island shorelines, focusing on the impacts of climate change and human activities. Furthermore, this study aims to provide reliable data and scientific insights that can support the United Nations' Sustainable Development Agenda, particularly emphasizing the sustainable development strategies for small island nations.

2. Methods

2.1. Study area

The research area in this present study encompasses a vast and diverse expanse (Figure 2) characterized by a complex and varied natural environment. It exhibits significant spatial differences in

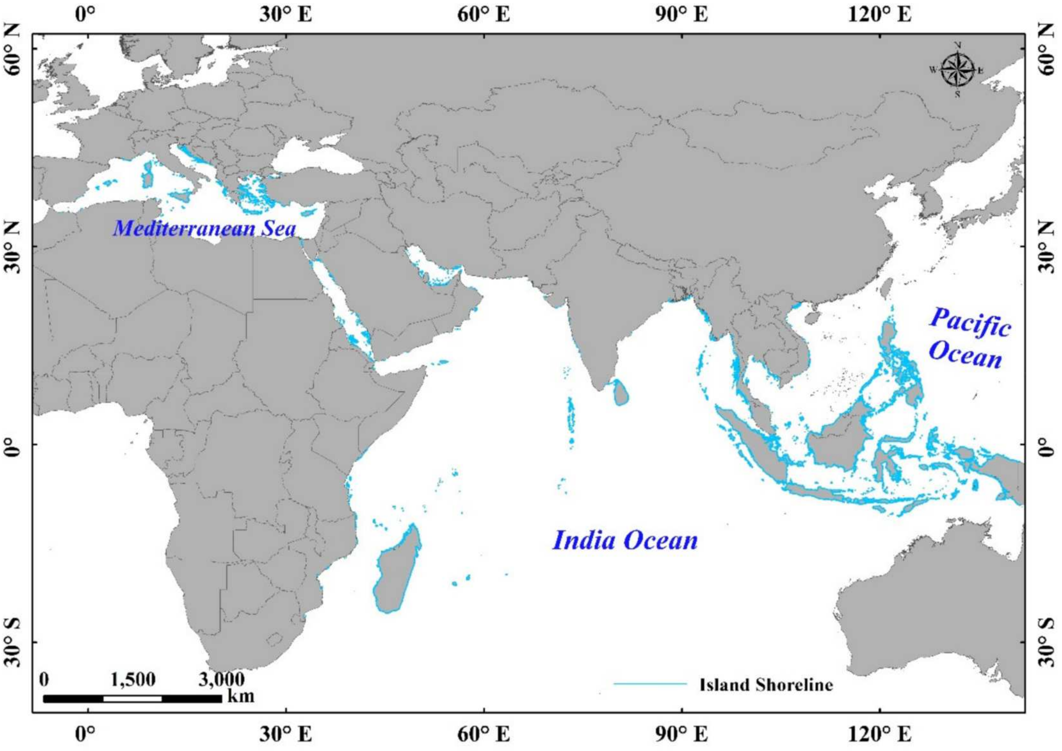


Figure 2. Illustration of the Study Area.

several key aspects, including climate conditions, topography, resource availability, ecological dynamics, and hydrological patterns. For instance, it includes regions with tropical rainforest climates, which are typically hot and receive high levels of rainfall, as well as areas characterized by extremely arid desert climates. Additionally, the area comprises coastal plains and river deltas, which are often resource-rich, as well as volcanic islands and deserts with limited ecological productivity.

The social and cultural environments of the study area exhibit significant variations across various dimensions, including political, economic, cultural, religious and educational aspects. Islands with developed economies, such as Singapore and Qatar, typically feature well-established infrastructure, high standards of living and advanced educational systems. In contrast, less developed islands, such as certain small islands in the Philippines, Indonesia and Africa, often possess rudimentary infrastructure and exhibit lower levels of educational attainment. These less developed islands may also host indigenous communities that maintain more traditional lifestyles.

This study is organized into eight distinct research units to comprehensively examine the spatiotemporal characteristics of shoreline changes on islands, which include the Philippine Islands, the Indonesian Archipelago, coastal islands near the Indochinese Peninsula, coastal islands in South Asia and West Asia, islands within the Red Sea, islands in the Mediterranean Sea, islands along the East Coast of Africa, and the Maldives.

2.2. Data sources

The spatial position of shorelines is constantly changing due to factors such as periodic tides, nearshore hydrodynamics, and sediment transport, rendering them dynamic rather than fixed entities (Hossain et al. 2022a; Mondal, Bandyopadhyay, and Dhara 2017). To address this variability, the concept of a ‘proxy shoreline’ has been introduced and widely accepted in the field. Among various proxies, the Mean High Water Line (MHWL) is regarded as the most appropriate indicator for assessing long-term island shoreline evolution (Dang et al. 2018).

The extraction of the Mean High Water Line (MHWL) is typically conducted using either automated/semi-automated methods or manual visual interpretation, each with distinct advantages and challenges. Automated and semi-automated methods are efficient and reusable. However, these approaches may encounter specific difficulties: (1) They often yield inconsistent and inaccurate shoreline delineations due to image noise and spatial resolution constraints, necessitating manual adjustments; (2) These methods require precise edge detection of the target shoreline, which can limit their use to certain environments; (3) The results reflect the waterline at the moment of image capture, requiring corrections with tidal and Digital Elevation Model (DEM) data, leading to uncertainties in both the tidal and DEM data and the correction procedure. Conversely, manual visual interpretation, though possibly less efficient and demanding more expertise, provides significant benefits. This method involves creating an extensive set of shoreline interpretation standards and principles for detailed delineation, allowing for more accurate shoreline information extraction. Importantly, this technique is versatile, applicable across various shoreline types and scales, and offers superior accuracy relative to automated methods.

In this study, we investigated a wide range of islands, each characterized by unique landforms, shoreline types, and developmental patterns. Given the limitations of existing automated extraction methods in accurately capturing the diverse shoreline features, we used a manual visual interpretation approach, which involved vectorizing the shorelines of islands using Landsat TM/ETM/OLI satellite imagery with 30-meter resolution. Our team conducted extensive fieldwork, comprising 623 survey points across mainland China and its islands, to gather empirical data from precise measurements of MHWL and the collection of a large photographic database (>7,000 images). By combining the color and texture features of the Landsat imagery with high-resolution reference images from Google Earth, we developed a detailed image library to enhance the visual interpretation of the MHWL on the islands.

Building upon the described methods, we successfully established a comprehensive dataset on island coastlines, such as coastline length, spatial positioning, development and utilization patterns, as well as national affiliations, from 1990 to 2020. This dataset, a first of its kind, includes details on coastline length, spatial positioning, and patterns of development and utilization, along with the national affiliations of the islands. We categorized the islands into three types: rocky, coral and sedimentary. Additionally, we classified shorelines into two primary groups: natural and artificial. Artificial shorelines were further subdivided into categories such as port, groin, reclamation, aquaculture, salt pan, transportation embankment, and urban shorelines. The accuracy of our shoreline extraction process is evidenced by an average positional error of 11.24 meters and a standard deviation of 22.54 meters (Figure 3), with this level of precision demonstrating the dataset’s ability to effectively meet the research requirements. For a detailed description of the shoreline data extraction, please refer to our previous work (Zhang et al. 2021; Zhang and Hou 2020).

2.3. Shoreline analysis

To investigate the changing hotspot areas, the Getis-Ord G_i^* analysis was performed. Getis-Ord G_i^* is a local spatial autocorrelation index that accurately detects high and low value aggregations using a distance weight matrix and enables the identification of statistically significant hotspots, including spatial distributions of cold or hot spots. G_i^* index, as formulated by Ord and Getis (Ord and Getis 1995), is utilized and described by Formula (1–5).

$$G_i^* = \frac{\sum_j^n W_{ij} x_j}{\sum_j^n x_j} \tag{1}$$

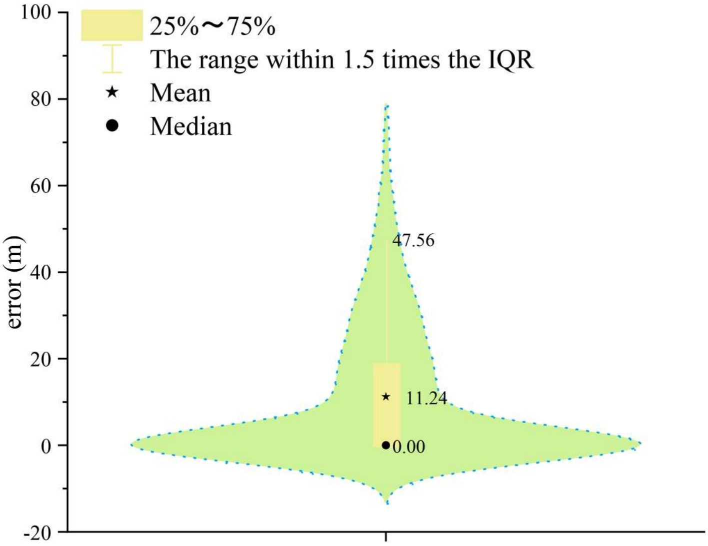


Figure 3. Distribution map of 1694 validation points.

Standardized G_i^* was used to obtain $Z(G_i^*)$:

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{VAR(G_i^*)}} = \frac{\sum_j w_{ij}x_{ij} - W_i\bar{x}}{s\sqrt{\frac{ns_{1i} - W_i^2}{n-1}}} \tag{2}$$

$$s^2 = \frac{\sum_j x_j^2}{n-1} - \bar{x}^2 \tag{3}$$

$$s_{1i} = \sum_j w_{ij}^2 \tag{4}$$

$$\bar{x} = \frac{\sum_j x_j}{n-1} \tag{5}$$

In Formula (1–5), x_j represents the attribute value of a spatial unit in a local scope, W_{ij} represents the distance weights between units i and j, W_i signifies the sum of all distance weights, and $\overline{x}$ denotes the average attribute value of all units in the region.

A positive $Z(G_i^*)$ indicates a high value for the neighboring unit i, while a negative $Z(G_i^*)$ suggests a low value for the neighboring unit i. Units with $Z(G_i^*) > 2$ are identified as areas of high-value aggregation, whereas units with $Z(G_i^*) < -2$ are recognized as areas of low-value aggregation.

To analyze the changes in island area resulting from shoreline modifications and to improve visualization across a larger spatial scale, we implemented a 30 × 30 km grid covering the entire study area. In each grid cell, statistical analysis was conducted to calculate the net change in island area. Using the natural break method, different threshold ranges were determined, visually representing the extent of net area change for islands in each grid cell. This method offers a comprehensive view of how shoreline changes impact island dynamics and enhances the visualization of these effects over a broader geographical scope.

3. Results

3.1. Shoreline dynamics

This research identified a total of 12,737 islands in 1990, 13,542 islands in 2000, 13,589 islands in 2010, and 13,629 islands in 2020. However, the data for 1990 did not include the Maldives region due to the lack of available imagery for that year. The corresponding total lengths of the island shorelines for these years were 196,700 km in 1990, 198,900 km in 2000, 199,500 km in 2010, and 200,200 km in 2020. Of these measurements, natural shorelines accounted for 192,500 km in 1990, 192,600 km in 2000, 190,500 km in 2010, and 189,000 km in 2020. In contrast, artificial shorelines extended over 4,211 km in 1990, 6,352 km in 2000, 9,006 km in 2010, and 11,285 km in 2020.

These data are presented in Table 1 (showing lengths) and Figure 4 (depicting proportions), which illustrate the spatial variations in island shoreline positions across different regions and time periods.

Over the past thirty years, the shorelines of islands in the studied region have shown notable spatial variations. The extent of shorelines that retreated landward amounted to 14,895.24 km, while those that advanced seaward were measured at 11,905.98 km, representing 7.57% and 6.05% of the total shoreline length, respectively. On a temporal scale, each of the three examined periods exhibited a greater proportion of eroding (landward retreating) shorelines than those that were expanding (seaward advancing). It was observed that the most significant changes in shoreline dynamics occurred between 2000 and 2010. Conversely, a period of relative stability in shoreline movements was observed from 2010 to 2020. This pattern of temporal variations was also distinct across various regions within the study area.

In terms of specific regions, the Indonesian archipelago exhibited the highest abundance of island shoreline resources, with relatively active changes observed over the past three decades. The proportions of eroding and expanding shorelines were recorded as 10.61% and 8.37%, respectively. The South Asia-Western Asia maritime area displayed the most dynamic behavior in terms of island shoreline variations in the entire studied region, with an exceptionally high proportion of eroding shorelines reaching 23.45% and an expanding shoreline proportion of nearly 10%. Additionally, a region of interest includes the central Indian Ocean, which encompasses the Lakshadweep Islands, the Maldives and the Chagos Archipelago, where a significant portion of shorelines exhibited seaward advancement, accounting for 9.11%. In the remaining regions, the proportions of the changed shoreline length did not exceed 5% of the total shoreline lengths.

Table 1. Spatial variations in the positions of island shorelines across various regions.

		Length(km)			
Unit	Dynamics	1990–2000	2000–2010	2010–2020	1990–2020
Philippine	Erosion	696.64	538.40	258.27	1381.68
	Accretion	286.17	811.31	198.75	1525.35
Indonesian	Erosion	5243.76	5407.59	2551.40	10525.48
	Accretion	2639.64	5186.29	2044.86	8297.99
Near Coast of Indochinese Peninsula	Erosion	339.45	596.98	164.44	692.25
	Accretion	199.90	466.13	289.14	751.72
South Asia and West Asia	Erosion	318.66	393.09	158.70	1230.88
	Accretion	197.29	231.85	96.55	523.31
Red Sea	Erosion	32.10	65.65	27.65	129.34
	Accretion	9.30	57.69	28.07	85.88
Mediterranean Sea	Erosion	40.27	60.77	8.44	254.04
	Accretion	67.43	83.86	12.03	164.28
East Coast of Africa	Erosion	295.81	250.99	91.97	626.31
	Accretion	178.89	152.13	59.40	382.87
Maldives	Erosion	/	36.69	9.17	55.25
	Accretion	/	86.04	30.17	174.56
Total	Erosion	6966.70	7350.16	3270.04	14895.24
	Accretion	3578.62	7075.30	2758.97	11905.98

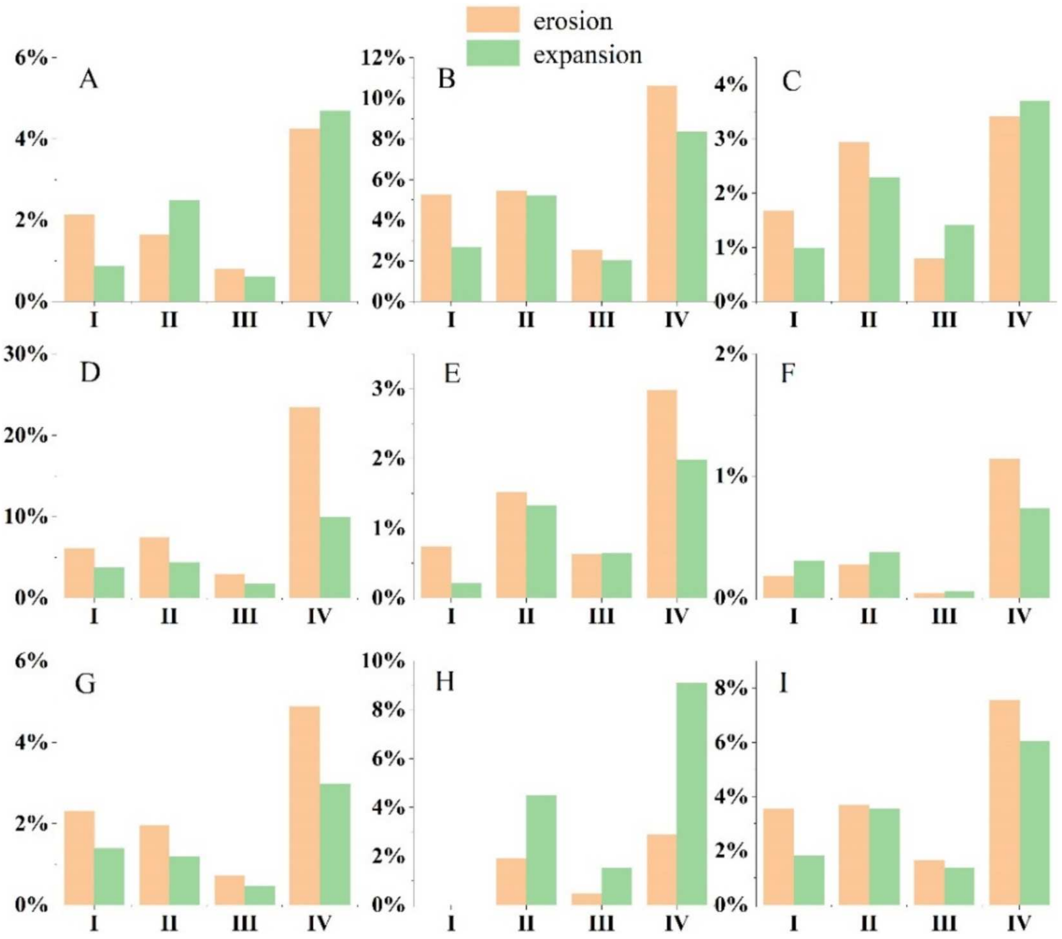


Figure 4. The proportions of shoreline position changes in various regions (I-1990-2000, II-2000-2010, III-2010-2020, IV-1990-2020. A- Philippine, B- Indonesian, C- Near Coast of Indochinese Peninsula, D- South Asia-Western Asia, E- Red Sea, F- Mediterranean Sea, G- East Coast of Africa, H- Maldives, I- Entire region).

Statistical analysis was conducted to examine the occurrence of shoreline dynamics in different types of islands and the influence of human disturbance (indicated by the presence of artificial shorelines). The results are presented in Table 2 and Table 3.

Table 2 indicates that bedrock and coral islands were the predominant island types identified. Over 30 years, around 12% of these islands experienced shoreline changes. Among them, alluvial islands exhibited the highest level of instability, with approximately 35% of their shorelines

Table 2. Shoreline Dynamics of Different Types of Islands

Types	Number	State	Number	Proportion /%
Rocky Island	6551	Erosion	440	6.72
Sedimentary Island	833		289	34.69
Coral Island	6245		843	13.50
Total	13629		1572	11.53
Rocky Island	6551	Expansion	470	7.17
Sedimentary Island	833		303	36.37
Coral Island	6245		989	15.84
Total	13629		1762	12.93

Table 3. Human Disturbance of Changing Islands.

State	Human Disturbance	Number	Proportion /%
Erosion	With	331	21.06
	Withou	1241	78.94
	Total	1572	100
Expansion	With	390	22.13
	Withou	1372	77.87
	Total	1762	100

undergoing erosion and accretion. In contrast, bedrock islands had relatively stable shorelines, with changes in only about 6–7% of shorelines. For coral islands, erosion and expansion affected 13.5% and 15.84% of shorelines, respectively.

Table 3 shows that over the past 30 years, fewer islands experienced landward erosion compared to those undergoing seaward accretion. Importantly, regardless of human disturbance, about 80% of islands underwent shoreline changes naturally, without human interference. This data offers insight into the dynamics of various island types and the impact of human activities on coastal alterations, enhancing our understanding of the complex interaction between natural phenomena and anthropogenic influences in island ecosystems.

3.2. Area dynamics

Spatial overlay analysis conducted for the four-phase islands in the years 1990, 2000, 2010, and 2020 revealed distinctive patterns of change. During the intervals of 1990–2000, 2000–2010, 2010–2020, and the entire span of 1990–2020, a total of 3,588, 7,008, 2,510, and 12,206 expansion patches were identified, respectively. Additionally, 4,056, 8,999, 2,335, and 117,794 erosion patches were observed during the same periods.

The dynamic changes in island area from the spatial variations in island shoreline positions are shown in Table 4.

Over the past three decades, the entire region experienced a cumulative increase in land area of 157.21 km^2 across more than 13,000 islands. However, this increase was not uniform over time. From 1990 to 2000, there was a net decrease in island area of 259.33 km^2. In the subsequent decades, the trend reversed, with net increases of 369.67 km^2 from 2000 to 2010 and 32.67 km^2 from 2010 to

Table 4. The variations in island area among different regions.

		Area(km^2)			
Unit	Dynamics	1990–2000	2000–2010	2010–2020	1990–2020
Philippine	Erosion	63.41	101.45	40.68	198.81
	Accretion	42.85	95.55	29.63	177.95
Indonesian	Erosion	720.64	675.67	404.76	1656.34
	Accretion	485.21	990.50	328.03	1699.73
Near Coast of Indochinese Peninsula	Erosion	39.76	70.93	17.58	178.70
	Accretion	61.32	133.27	90.38	284.98
South Asia and West Asia	Erosion	105.01	86.82	39.53	238.27
	Accretion	78.46	79.49	45.88	230.18
Red Sea	Erosion	3.46	2.62	1.32	6.72
	Accretion	0.45	3.77	33.78	44.23
Mediterranean Sea	Erosion	3.69	2.02	0.72	13.18
	Accretion	11.41	4.45	1.67	18.14
East Coast of Africa	Erosion	32.49	49.45	9.56	119.85
	Accretion	29.41	38.06	7.26	90.13
Maldives	Erosion	/	1.61	0.46	1.44
	Accretion	/	15.15	10.67	25.20
Total	Erosion	968.45	990.57	514.62	2413.31
	Accretion	709.12	1360.24	547.30	2570.53

2020. These variations in island areas can be attributed to a mix of socio-economic drivers and natural environmental factors.

In regional analysis, the Philippines archipelago, islands in the South Asia-Western Asia maritime area, and islands in the eastern African waters showed a net decrease in area, with reductions not exceeding 30 km^2. In contrast, the Indonesian archipelago, islands along the Indochinese Peninsula coast, the Maldives and islands in the Red Sea and Mediterranean Sea experienced a net increase in area. Notably, the coastal waters of the Indochinese Peninsula had the most substantial gain, with an increase of 106.28 km^2 over the 30-year period.

From a temporal viewpoint, the Philippines archipelago and islands in the eastern African waters consistently showed a net decrease in area across the three decades. In contrast, the coastal waters of the Indochinese Peninsula, islands in the Mediterranean Sea, and the Maldives exhibited a net increase in area during the same period. However, the Indonesian archipelago displayed a dynamic increasing and decreasing pattern in area over time.

To visually represent the spatial effects, Figure 5 presents grid data (30 km × 30 km) illustrating the net changes in island area.

During the four time periods of 1990–2000, 2000–2010, 2010–-2020, and 1990–2020, a total of 1313, 2292, 984, and 2592 grids were generated, respectively, to cover the changing areas of the islands in the study region. Within these grids, 827, 1002, 411, and 1173 experienced a net decrease in area, whereas 486, 1290, 573, and 1419 showed a net increase.

An overlay analysis was performed to accurately delineate the spatial and temporal dynamics of coastal changes and quantitatively illustrate the alterations in island land-sea distribution. This method pinpointed locations where islands receded from the mainland and extended into the sea during each studied period. The identified patches of change were weighted according to their area, which assisted in spatial clustering. This process was crucial for pinpointing hotspots of island erosion and expansion. Figures 6–9 display the spatial distribution of these hotspots. Utilizing this method provides a detailed insight into the spatial and temporal fluctuations of island shorelines, enabling a quantitative evaluation of land area changes. These insights are vital for a deeper understanding of the intricate interactions between islands and their adjacent marine ecosystems.

4. Discussion

4.1. Spatiotemporal characteristics of shoreline dynamics

Variability in coastal changes exhibits distinct spatiotemporal characteristics (Purkis et al. 2016). Islands, defined as geographically delimited landmasses surrounded by water, exhibit a markedly pronounced spatiotemporal diversity in their coastal dynamics (Rankey 2011). Recognizing and understanding this distinctive characteristic is vital for evaluating island vulnerability and devising strategies for their sustainable development (Mann, Bayliss-Smith, and Westphal 2016).

The study of island shoreline evolution is typically conducted across seasonal, interannual and decadal time scales. Seasonal variations significantly influence island shorelines, often causing substantial spatial changes, primarily due to strong monsoon effects (Kench and Brander 2006). The morphological sensitivity of these shorelines to short-term changes in boundary wind and wave conditions, primarily influenced by local wind patterns, is a key factor in the movement of sediments along island coasts (Beetham and Kench 2014; Dawson and Smithers 2010). On an interannual scale, island shorelines exhibit periodic responses to fluctuations in water levels and wave conditions, which leads to a cyclical reorganization of these shorelines (Cuttler et al. 2020). Such processes often result in minimal net changes in the overall size of the islands (Kench and Brander 2006). Furthermore, the ability of island beaches to recover after intense storm surges demonstrates their inherent self-adjustment capabilities. Despite the possibility of substantial short-term erosion that may temporarily alter long-term evolutionary patterns, islands tend to revert to their former

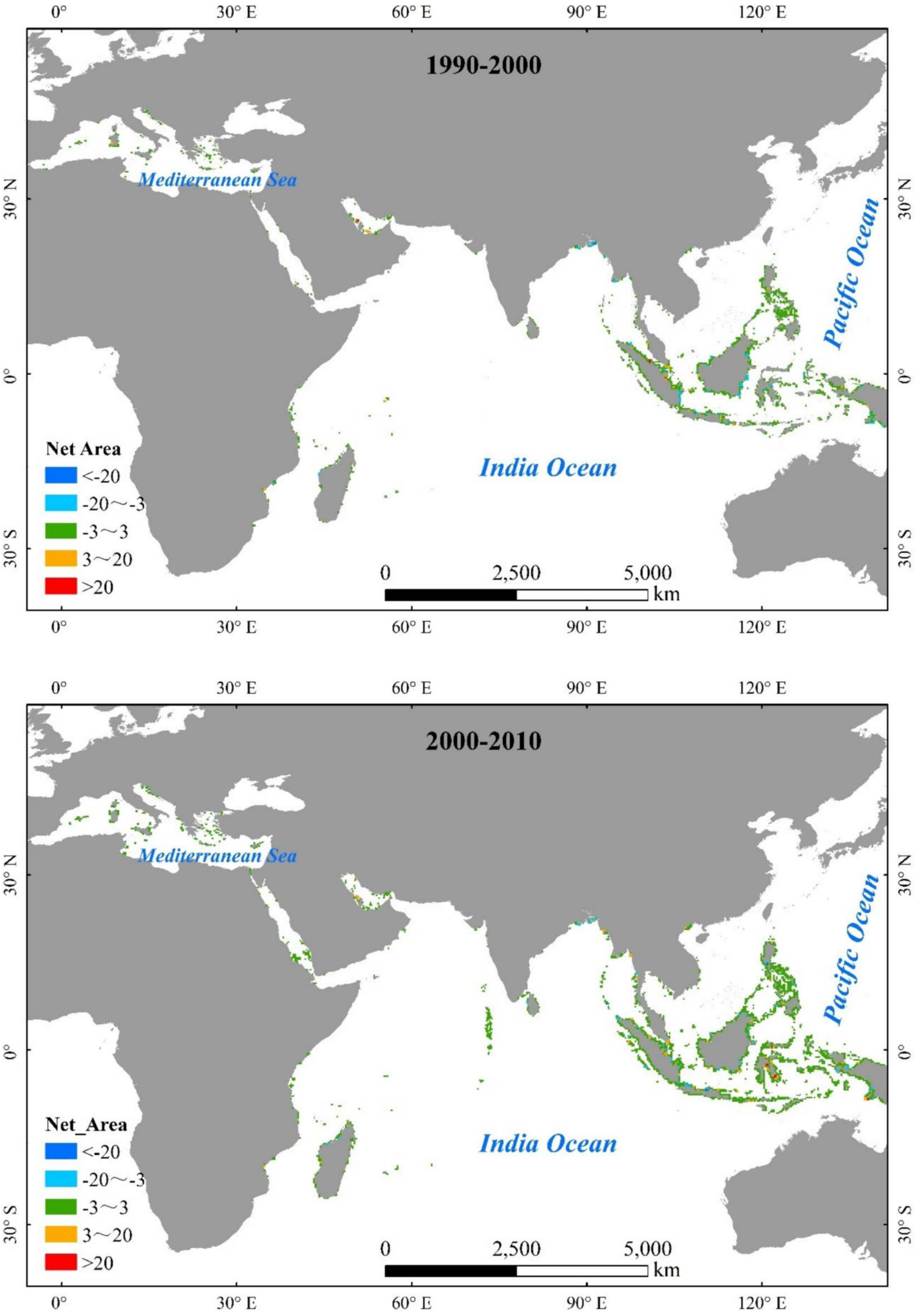
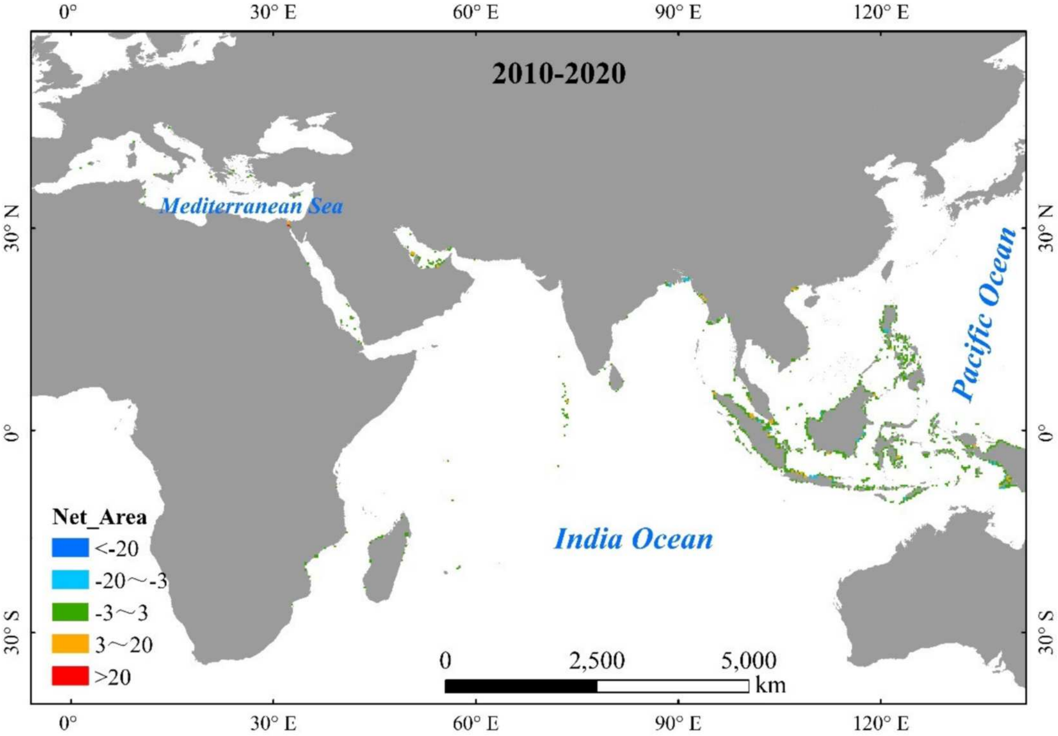


Figure 5. Net changes in island area during the different time periods from 1990 to 2020.



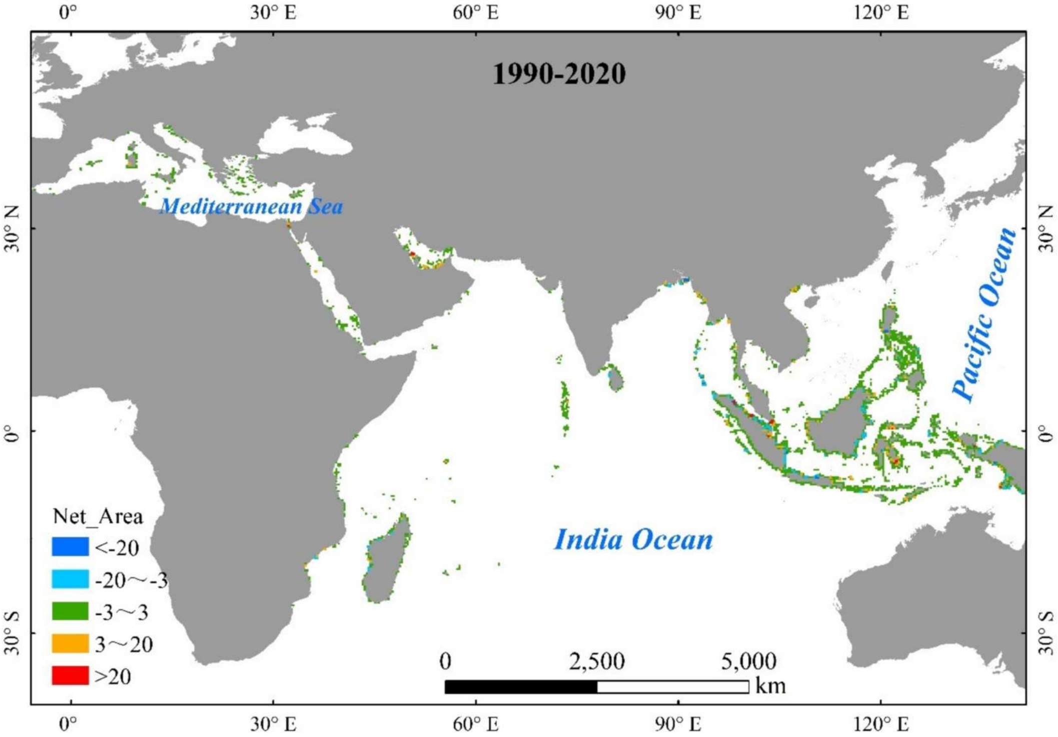


Figure 5. *Continued.*

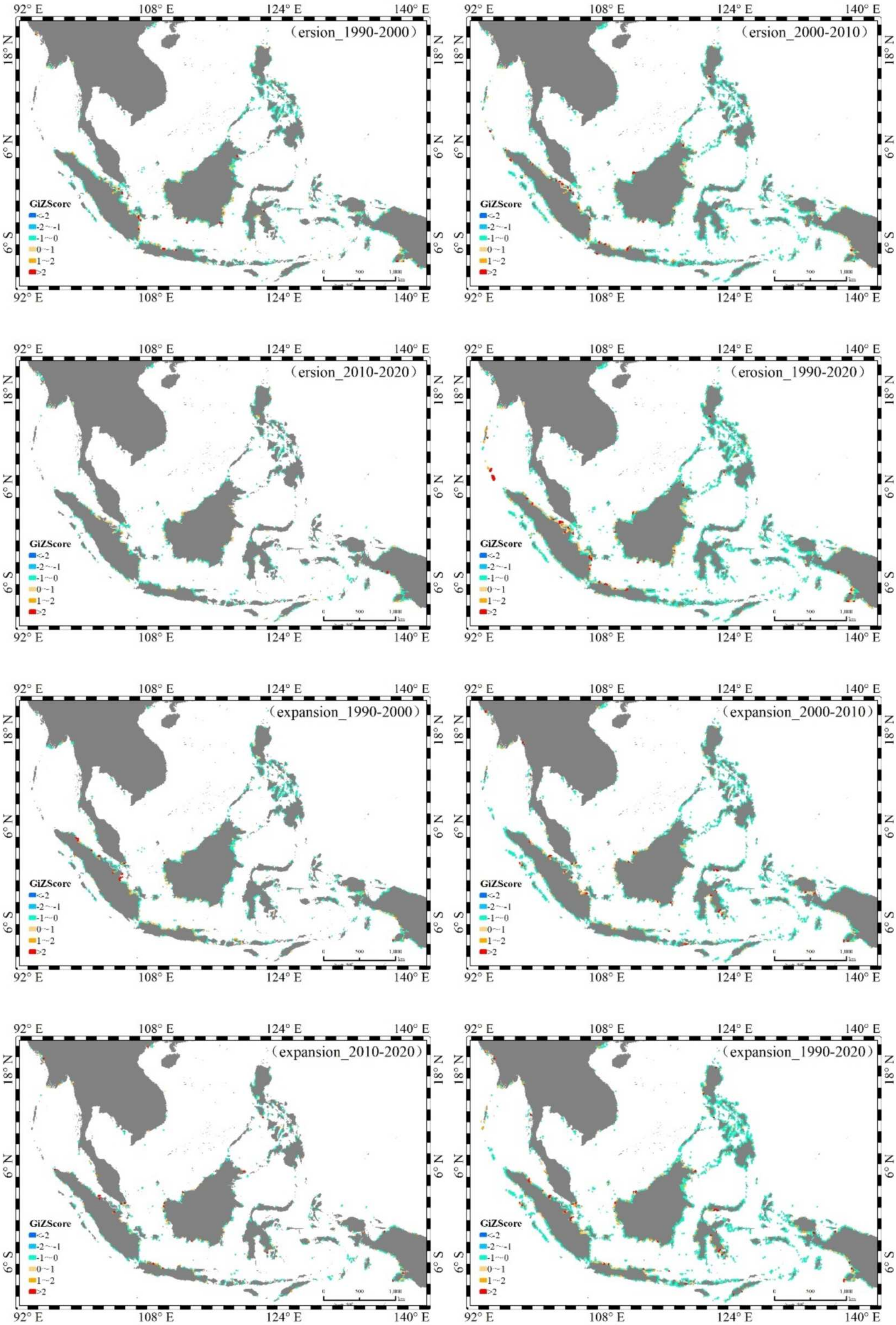


Figure 6. Hotspot distribution of island area changes in the Southeast Asian region.

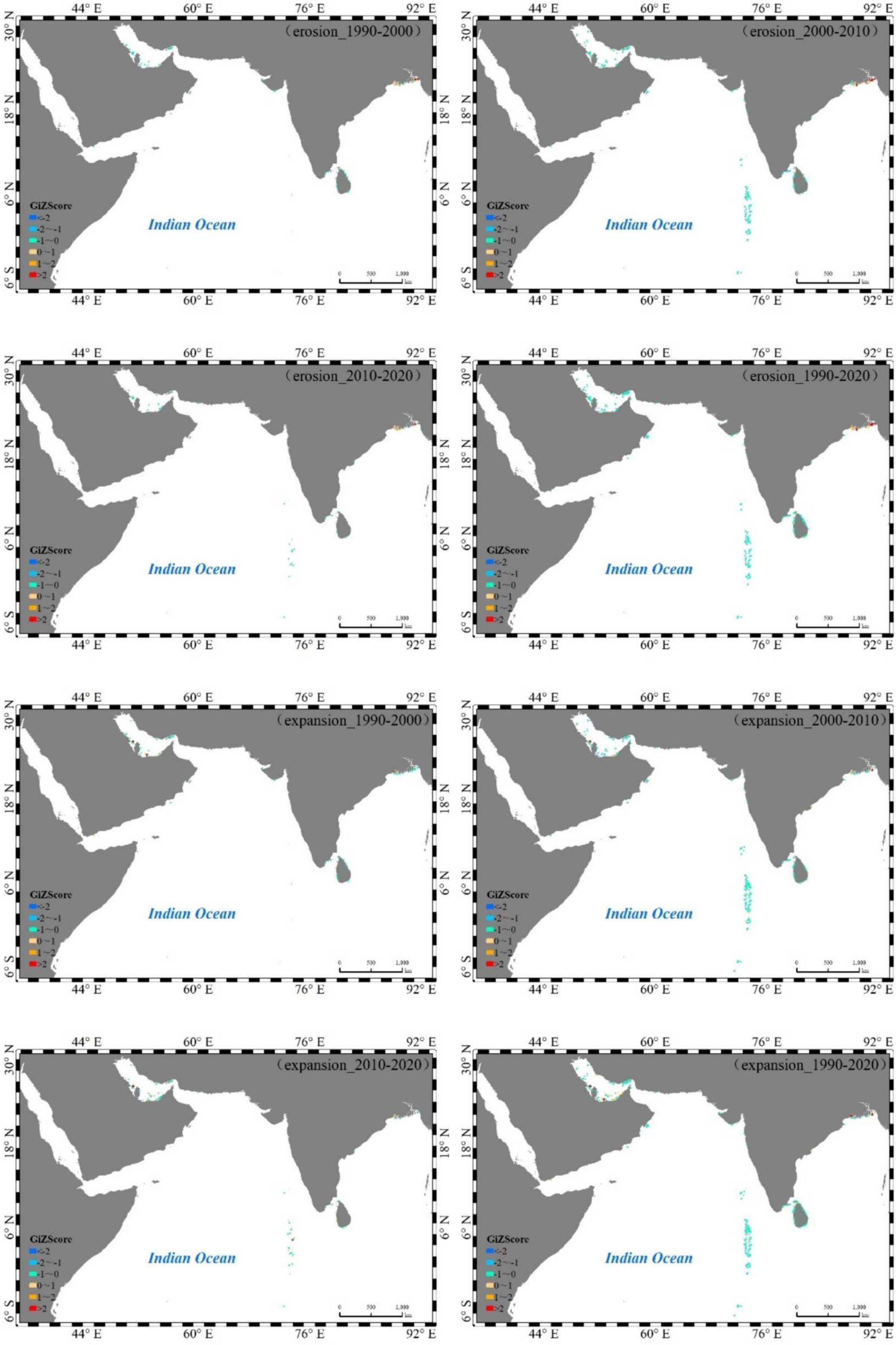


Figure 7. Hotspot distribution of island area changes in the South Asia-Western Asia regions.

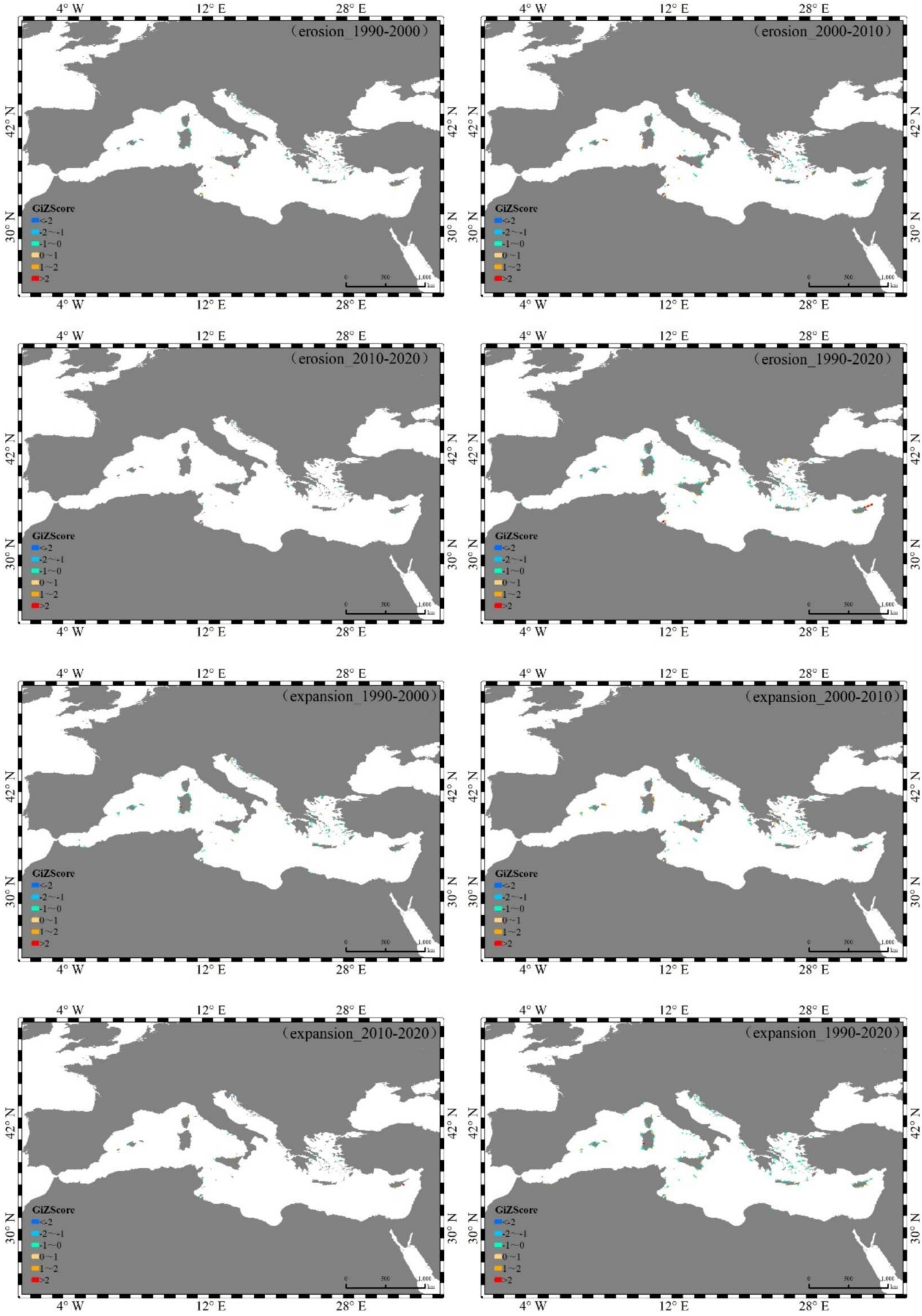


Figure 8. Hotspot distribution of island area changes in the Mediterranean Sea.

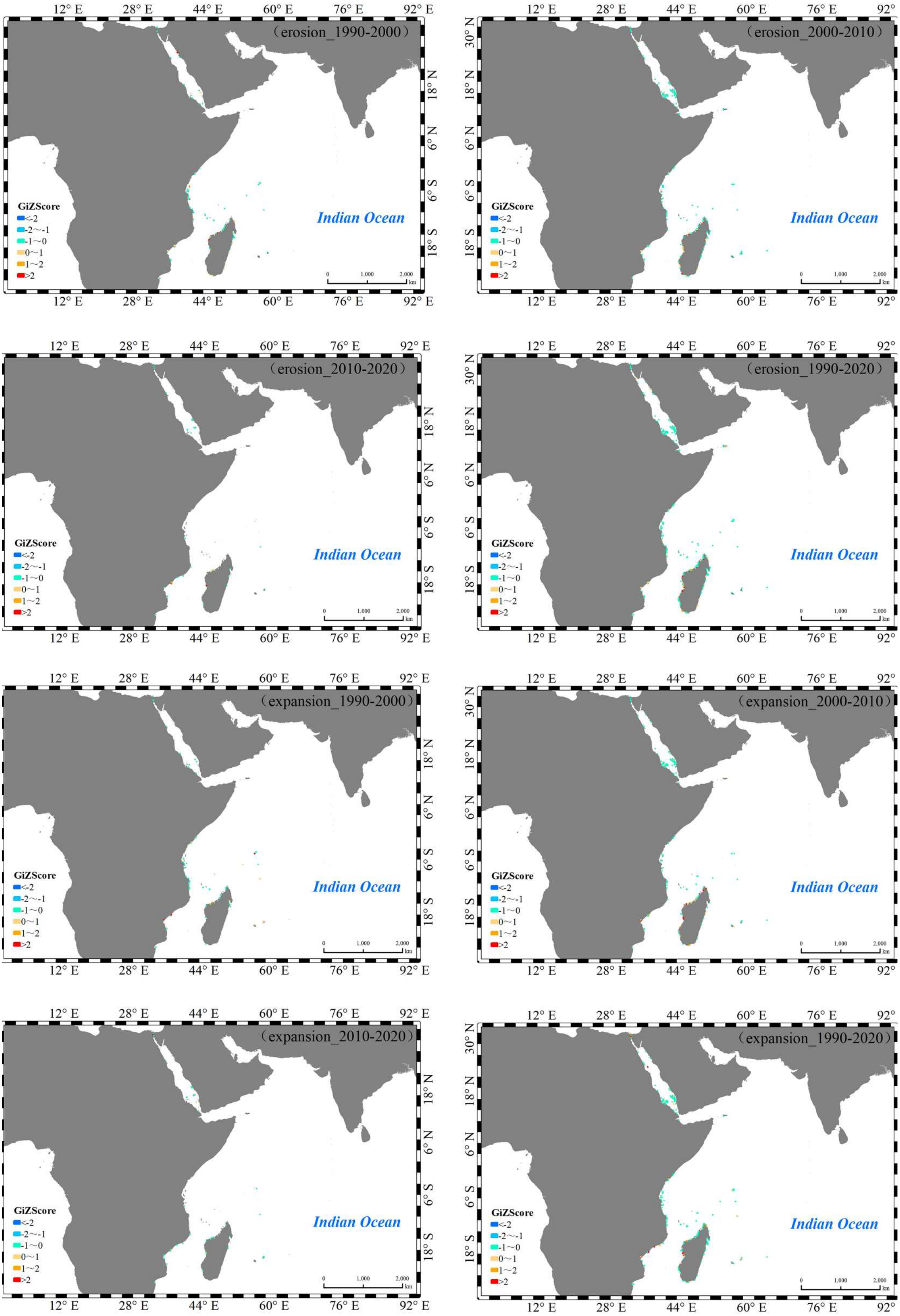


Figure 9. Hotspot distribution of island area changes in the eastern African waters.

states and trends within several years (Johnston, Cooper, and Olynik 2023). The frequency at which shoreline observations are made is crucial. Some researchers argue that the increase in the frequency of observations, rather than sea-level rise, is more indicative of observed shoreline erosion (Dawson 2021). As a result, it is suggested that remote imagery, even when used at a lower sampling frequency, is adequate for detecting significant morphological changes in island beach landscapes (Mann and Westphal 2014).

Given the highly dynamic nature of island coastal environments, which are periodically affected by monsoons and varying marine conditions, this study selected a 10-year interval for assessing island shorelines to more accurately reflect the long-term evolutionary trends on a broad spatial scale. Despite using this decadal approach, our findings reveal significant temporal variations. Specifically, the interval from 2000 to 2010 was identified as the most active period for changes in island shorelines over the past thirty years. In contrast, the following decade, from 2010 to 2020, shows a period of relative stability.

Shoreline position changes exhibit considerable spatial differences, which are influenced by a combination of human activities and natural elements (Schmelz and Psuty 2022). Variations in sediment supply and transport patterns are identified as the primary drivers for these variations (Duvat, Volto, and Salmon 2017b; Hu and Wang 2022; Testut et al. 2016).

The comprehensive analyses of this present study demonstrate marked spatial disparities in shoreline dynamics. On a broader spatial scale, the Southeast Asian archipelagos show more pronounced shoreline changes than those in the Mediterranean Sea. When focusing on individual islands, such as Sumatra, the eastern coast was observed to experience more activity than the western coast. Conversely, the eastern coast of Madagascar maintains relative stability compared to its more dynamic western coast. At a regional level, floodplain islands in various river deltas display significant differences in erosion or accretion patterns. Additionally, in bays or straits with high human population density, the impact of human activities often intensifies shoreline dynamics.

4.2. Driving mechanisms of shoreline dynamics

The main factors influencing changes in island shorelines can be categorized into anthropogenic and natural elements. Anthropogenic factors include population growth, urbanization, aquaculture, port construction, dam construction, airport and military base development, deforestation, and commercial sand mining (Collin et al. 2018; Duvat and Pillet 2017; Hai et al. 2018; Valderrama-Landeros and Flores-de-Santiago 2019). Natural factors encompass coastal material composition, geomorphology, coastal ecosystem dynamics (i.e. mangroves, salt marshes, coral reefs), sea-level rise, storm surges, tsunamis and earthquakes (Fabris 2019; Lithgow et al. 2020; Orejarena-Rondón et al. 2019; Payo et al. 2020). Figure 10 illustrates remote sensing images that show shoreline changes in four different settings, with the predominant factors being sediment transport, coastal flooding, aquaculture development, and harbor construction.

The dynamics influencing island shoreline changes can be divided into two main pathways. The first involves the direct human occupation of coastal zones, leading to shifts in the spatial position and type of land use along shorelines, which includes activities such as land reclamation, deforestation and the intrusion of saltwater into freshwater systems. The second pathway is shaped by alterations in sediment supply and transport. For instance, dam construction can reduce sediment flow to the sea, while human modifications of river channels and estuaries can directly alter sediment availability (Gomby 2017). Additionally, natural factors such as monsoons, wave dynamics, and nearshore hydrodynamics play a significant role in changing sediment transport patterns, thereby affecting the configuration of island shorelines (Beetham and Kench 2018).

Shorelines exhibit distinct patterns of change in response to various influencing factors. For instance, the impact of natural elements on the spatial positioning of coastlines can be extensive, yet the degree of influence could be relatively small and may not alter other shoreline

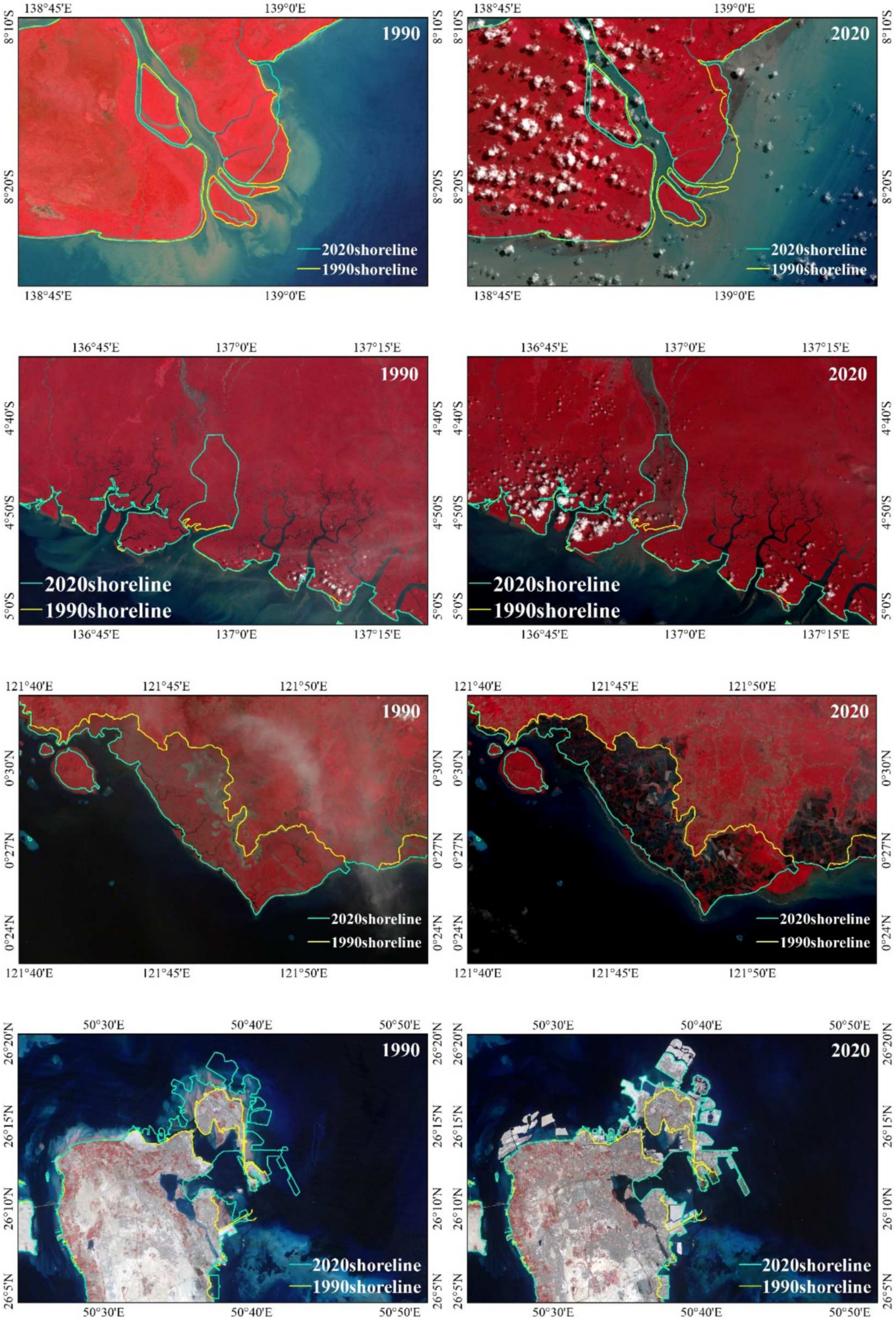


Figure 10. Shoreline changes due to various influencing factors.

characteristics. In contrast, human activities typically have a localized but significant effect on shorelines. These activities not only alter shorelines' spatial positioning but also change their development and potential utilization, with such impacts usually being irreversible. Importantly, natural events such as storm surges, coastal flooding, river cutoffs and vegetation regeneration can lead to significant shoreline retreat or expansion over specific periods.

Moreover, the data results suggest that sea-level rise has not been a widespread cause of erosion for island shorelines in the studied region. Presently, it is considered one of the contributing factors to shoreline erosion but not the predominant one.

4.3. Future fate of islands under SLR

Regardless of the historical or current impacts of sea-level rise on islands, the latest IPCC AR6 WGI assessment reports with high confidence that all evaluated coastal climatic impact drivers, including relative sea-level rise, coastal flooding and coastal erosion, are projected to intensify in almost all regions globally by mid-century. Thus, these risks are unavoidable for islands, particularly small island states, thereby underscoring the urgent need for adaptation strategies to address the risks posed by climate change to island communities and their assets. The extreme sea level data for four experimental sites in the Indian Ocean are shown in Figure 11.

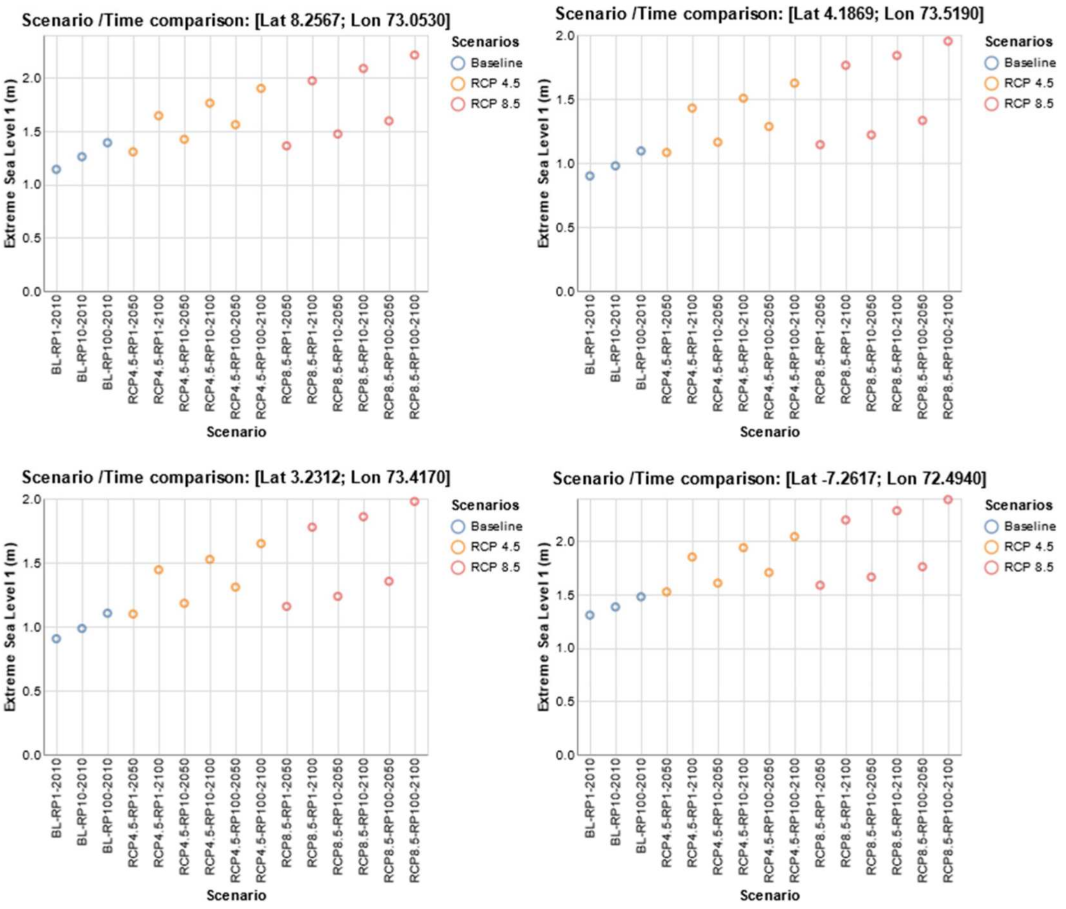


Figure 11. Data on extreme sea level rise scenarios for the experimental sites in Lakshadweep Islands, Maldives Islands and Chagos Islands in the Indian Ocean (data sourced from the Coastal Futures interactive viewer http://coastal-futures.org/)

The risks associated with sea-level rise for islands are complex and significant. The primary concern is the severe threat to the natural environment of island nations. Sea-level rise leads to shoreline retreat and intensifies coastal erosion, posing a direct threat to the ecological integrity of these areas. Due to their restricted land area and often low elevation, islands are especially vulnerable to inundation, which raises concerns about the loss of ecological diversity, the degradation of coastal wetlands and coral reefs, and the survival of marine biodiversity and rare species.

Moreover, islands face considerable challenges regarding water resources and freshwater scarcity. Generally dependent on groundwater and precipitation for their freshwater supply, island nations are experiencing the intrusion of saltwater into their aquifers as a consequence of the rise in sea levels. This intrusion reduces the availability of freshwater resources. Additionally, frequent floods and storm surges contribute to contaminating these already limited freshwater sources. Consequently, island nations are dealing with an increasingly strained water supply and growing scarcity, which directly affects the livelihoods of their residents and agricultural productivity.

The economic and social repercussions of sea-level rise on islands are extensive and varied. The tourism industry, often a crucial economic backbone for these nations, faces significant risks due to shoreline retreat and coastal erosion, leading to the deterioration of tourist facilities and resorts, resulting in a decrease in tourist arrivals and revenue. Furthermore, issues such as food security, energy supply, and infrastructure durability present serious challenges for island countries. These challenges have far-reaching effects on social stability and economic development. As a result, island nations may have to contemplate migration or adopt adaptive strategies to cope with changing environmental conditions. Such potential population displacement can lead to complex social and cultural issues, intensify conflicts over resources, and contribute to social unrest.

4.4. Adaptation for islands

Focusing solely on risks without considering adaptation and mitigation strategies contradicts the principles of sustainable development (David et al. 2021). Numerous studies have shown that the application of scientifically informed adaptation measures can prevent significant alterations in the structure and morphology of island shorelines in the upcoming decades (Ahrendt 2001) and suggest that even low-lying atolls could maintain stable environments suitable for human habitation well into the next century (Kench, Ford, and Owen 2018).

Seawalls, as forms of hard engineering structures, act as direct barriers against waves and storm surges, offering effective protection for coastal areas (Jinoj et al. 2021). Studies on the eastern coast of Sumatra, Indonesia, have demonstrated that seawall construction can significantly reduce beach erosion rates from 10 meters over 14 years to virtually none in the same period (Sandhyavitri et al. 2019). The Maldives, a small island developing state, has shown that coastal stabilization measures not only safeguard fragile ecological systems but also support sustainable economic growth (Corral and Schling 2017). Nonetheless, the effectiveness of hard protection measures such as seawalls in island settings remains academically debatable. Critics argue that such interventions are often unsuccessful and may even worsen shoreline erosion, failing to safeguard property, land and food production (Klöck, Duvat, and Nunn 2022). Particularly in remote locations, the construction of seawalls is not seen as a viable short-term response to emerging challenges and is considered ineffective in assisting coastal communities to adapt to long-term shoreline changes (Nunn, Klöck, and Duvat 2021).

At present, there is a tendency for island communities to accept and widely adopt seawalls as rigid coastal protection measures, leading to significant imitation and diffusion of this practice. However, this approach carries considerable risks. For instance, constructing seawalls is a highly complex task that demands expertise in hydrodynamics, geology, engineering, and climatology. In the absence of substantial data and scientific justification, the effectiveness of seawalls in protecting island shorelines can be doubtful, and their implementation may compromise the safety of the islands.

Island communities have a range of strategies available to address the impacts of rising sea levels. For coastal protection, restoring and preserving coastal wetlands, coral reefs, and seagrass beds can act as natural defense mechanisms, offering more effective and sustainable solutions (Montgomery et al. 2019). In managing freshwater resources, sustainable water management strategies are crucial and include enhancing water use efficiency, collecting and storing rainwater, and utilizing desalination techniques. Adopting water-saving measures, such as using water-efficient devices, improving irrigation systems, and managing agricultural water more effectively, can significantly reduce the demand for freshwater resources. Regarding energy management, prioritizing the use of renewable energy sources, such as solar, wind, and tidal energy, is essential to decreasing dependence on traditional fossil fuels and lowering greenhouse gas emissions. Promoting improvements in energy efficiency is also critical, which includes enhancing the energy efficiency of buildings, encouraging the use of energy-saving devices, and implementing energy management systems. Furthermore, community engagement and education play a vital role in this aspect. Strengthening community participation involves raising public awareness and building knowledge and capacity to tackle climate change, such as encouraging residents to develop and implement ecological conservation and adaptation measures. Climate change education should be promoted through activities and training in schools and communities to improve public understanding of climate change and sea-level rise issues.

International cooperation and assistance are essential for effectively implementing adaptation measures and achieving sustainable development in island nations. Most island countries, particularly small island developing states (SIDS), confront economic challenges, making the success of scientifically supported adaptation measures reliant on international collaboration and aid. Thus, island nations should actively engage in international climate negotiations, notably within frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Participation in these platforms is crucial to promote their interests and acquire essential support. Additionally, strengthening regional cooperation is of fundamental importance, which involves active participation and contribution to regional organizations like the Pacific Islands Forum (PIF) and the Caribbean Community (CARICOM). The establishment of platforms for information exchange and joint efforts, along with the development of adaptation strategies in a regional context, is vital for addressing the unique challenges island nations face due to climate change.

The United Nations, along with international organizations, developed nations and advanced developing countries, bear a significant responsibility in this context. These bodies can substantially support small island developing states by adhering to the United Nations Sustainable Development Agenda, which may encompass financial assistance, evident in contributions to mechanisms such as the Global Climate Fund and Green Fund. Additionally, the transfer of technology and expertise, particularly in areas such as island engineering, flood protection technologies and desalination processes, is crucial. Collaborative efforts in scientific research also play a key role. These initiatives aim to strengthen the adaptive capacity of small island nations against climate change impacts and foster their sustainable development.

4.5. Study limitations

This study encompasses a vast research area, with a diverse distribution of islands characterized by clustering and discontinuity. The dynamic analysis presented in this article offers insights into island coastlines from multiple perspectives and across various spatial and temporal scales, but numerous questions still remain unanswered and merit further investigations. Our methodology involved extracting coastline data across four distinct years spanning a decade, and although such an approach is instrumental in capturing long-term trends in island coastline evolution, it may inadvertently lead to either an underestimation of coastline changes in certain areas, attributable to the considerable time span between data points. Thus, while these findings may contribute to our understanding of the long-term evolutionary trends of island coastlines, they could be insufficient for comprehending short-term change characteristics.

5. Conclusions

This study developed a comprehensive analytical framework to examine island shorelines, integrating remote sensing, GIS, and mathematical approaches. The research identified statistically significant changes in island shorelines over the past three decades, reflecting climate change impacts. These relatively modest changes account for about 12% of the total observed changes (6.05% expansion seaward and 7.57% retreat landward). The study also identified specific hotspots of pronounced shoreline changes, often in densely populated estuarine deltas. In these areas, changes are typically marked by disorganized expansion or submergence of aquaculture ponds and wetland reclamation. These findings are crucial for disaster prevention and mitigation strategies in estuarine delta regions.

The transformation of island shorelines results from a combination of natural elements and human activities. The key natural factors include the inherent composition of islands, sediment transport processes and the self-regulating features of mangrove ecosystems. At the same time, significant human-driven factors influencing the seaward expansion of island shorelines encompass urban growth, the vigorous development of port economies, and the increase in aquaculture activities.

Contrary to initial assumptions, our empirical data does not conclusively link the widespread erosion of island shorelines primarily to historical sea-level rise, suggesting that human activities might mask the effects of sea-level rise. Based on a thorough analysis of current data and consideration of future sea-level scenarios, we believe that sea-level rise will continue to pose a significant challenge to island communities and recommend these communities to adopt scientifically validated strategies as these could be crucial for their sustainable survival and development. On the other hand, failing to adapt proactively or resort to short-lived and hasty measures could lead to severe consequences for small island states and regions.

In summary, this research has established a distinctive dataset concerning island coastlines, revealing the trends and dynamics of island shoreline changes influenced by climate change and human activities over extensive temporal and spatial dimensions. We have examined the factors driving these shoreline alterations and investigated the risks islands confront with impending sea-level rise. Additionally, we suggest targeted strategies for island response and adaptation. Collectively, this research findings could be crucial for promoting the sustainable development of islands and offer important insights for concerned nations and organizations.

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Data availability

Data will be made available on request.

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