Hotspot Analysis of Global Piracy and Armed Robbery Incidents at Sea: A Decadal Review of Regional Vulnerabilities and Security Strategies

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Abstract

Maritime piracy (MP) and armed robbery at sea (ARS) pose significant threats to global maritime security, affecting trade and economic stability. These incidents, whether successful or not, can lead to loss of life, and long-lasting mental and psychological health impacts on ship crews. This study utilizes the spatial density analysis via the Geographic Information System to explore the global distribution of MP and ARS incidents from 2010 to 2021. Analysing 3,241 incidents that occurred across the globe over two distinct periods, 2010- 2015 and 2016-2021, the study has identified and visualized hotspot areas globally, revealing the geographic patterns with an aim to assist the strategic mitigation of these threats. Regional analyses indicate a shift in piracy activities; Southeast Asia shows a decrease in attacks (halved) in the Straits of Malacca coupled with persistent threats in the Singapore Strait. Conversely, East Africa has seen a reduction in piracy due to effective international maritime patrols and legal frameworks, although the area remains volatile due to persistent socio-economic and political challenges. The findings demonstrate that geopolitical instability, legal gaps, and economic disparities significantly contribute to MP and ARS. The study advocates for sustained international cooperation, enhanced legal measures, and continuous monitoring to effectively combat these threats. Future research could benefit from a more detailed temporal analysis, using different methodological approaches (*e.g.*, incorporating time-series analysis) to capture seasonal or short-term variations in incident occurrences. This could provide additional insights into the dynamics of piracy and armed robbery incidents and inform policy and security strategy adjustments.

Keywords: Maritime piracy; Geographical Information System; Kernel density analysis; Hot spot mapping; Maritime security

1. Introduction

Maritime transportation forms the backbone of global trade and continues to be an indispensable force driving economic growth (Bai et al., 2021; Jiang and Lu, 2020; Liu et al., 2022). Throughout history, maritime piracy has posed a threat to maritime trade and the peace

of the world's oceans (Nwokedi et al., 2022; Shepard and Pratson, 2020; Wambua, 2022). It is also one of the oldest issues in international maritime law and still is a significant problem threatening trade and security (Bryant et al., 2014; Murphy, 2013; Pristrom et al., 2013). In addition to the traditional view that the primary motivation behind maritime piracy (MP) and armed robbery at sea (ARS) is financial gain (Gaibulloev and Sandler, 2016; Pristrom et al., 2016), recent studies suggest that these acts are often driven by a complex mixture of financial, political, ideological, and social factors (Liang et al., 2024; McNeill, 2023; Okafor-Yarwood and Onuoha, 2023; Schneider, 2020). On the other hand, it is accepted in the literature that motivation is an important determining factor in distinguishing the types of maritime security crimes. If the motivation is financial, such incidents are classified as piracy and armed robbery at sea. However, if the motivation is driven by political and ideological purposes, they are categorized as maritime terrorism (Honniball, 2015; Møller, 2009). These attacks can lead to severe consequences, ranging from loss of human life to national and international economic impacts, environmental disasters, and serious political issues (Gong et al., 2023; He et al., 2023; McNeill, 2023).

The cost of piracy activities is a significant but highly complex issue, and there is no single agreed-upon value in the literature on this matter. The One Earth Future (OEF) Foundation conducted a large-scale study in 2011 as part of the Oceans Beyond Piracy project, quantifying the cost of piracy. They estimated that the MP and ARS issues impose an annual cost of $7 to $12 billion on the global economy. The majority of this cost is attributed to insurance premiums ($460 million to $3.2 billion), re-routing ships ($2.4 to $3 billion), security equipment ($363 million to $2.5 billion), and naval forces ($2 billion) (Bowden and Basnet, 2011). Report published by Stable Seas, a transnational maritime security research organization, noted that in 2021, 12 countries in West Africa spent a total of $550 million on maritime expenditures to combat the MP and ARS issues, with 69% of this expenditure covered

by Nigeria. The report indicates that between 2011 and 2021, these 12 countries collectively spent $4.5 billion on anti-piracy measures (Bell et al., 2021). Currently, many studies in the literature estimate the annual cost of piracy incidents to be around $25 billion (Bensassi and Martínez-Zarzoso, 2012; Molina and McDonald, 2019; Zhang et al., 2024). The MP and ARS issues are continuously evolving ones that can vary in scale depending on a variety of factors. Consequently, the economic damage it causes to the global economy fluctuates each year. Understanding the regional economic impact of MP and ARS would provide meaningful insights for relevant stakeholders.

Each attack, whether successful or not, can result in the loss of life, robbery of ship/crew, and long-lasting mental and psychological health problems (Bateman, 2011; Pristrom et al., 2016). The fact that modern maritime piracy is much more violent, complex, and widespread than in the past is a concerning situation (Bryant et al., 2014). Today's piracy attacks are much more severe compared to previous years (Schneider, 2020; Talha et al., 2023). Whereas pirates previously used weapons such as knives, sticks, and daggers, today they often use heavy weaponry (Chalk and Hansen, 2012). The issue of maritime piracy and armed robbery at sea, which seriously threatens maritime security, has remained unresolved over the years, and continues to persist today.

The United Nations Convention on the Law of the Sea (UNCLOS) defines maritime piracy as “acts of violence, detention or depredation, and plundering committed against another vessel, person, or property on the high seas” (IMO, 2009; Ishii, 2014; Keyuan and Jing, 2020; UN, 1982). When these actions occur within a state's territorial waters, under its jurisdiction, they are classified as armed robbery at sea. The definition of maritime piracy is quite narrow, limited only to acts conducted on the high seas from one vessel to another (Treves, 2009; Von Hoesslin, 2012).

Various geographical and political factors have provided the ground for pirates to conduct their attacks over centuries. The geographical structure of countries and continents is a significant factor affecting maritime piracy attacks. The proximity of countries with different economic and political structures within the same geography lays the groundwork for maritime piracy (Hastings, 2012). One of the factors encouraging people towards armed robbery at sea and maritime piracy is the absence of a properly functioning state and enforcement system. Attacks stemming from civil war, political vacuum, discrimination, and chaos are predominantly concentrated in the African region, especially around Somalia. Over a decade, the lack of an effective government in Somalia has not only made maritime piracy a profitable opportunity for committing crimes but also allowed piracy to evolve into a form of organized crime. The extent of piracy in the region usually demonstrates the Somalian State's lack of strong law enforcement forces. The area is almost entirely without naval forces, preventing the establishment of adequate order, a chain of command and emergency intervention in case of any occurrence (Kayisoglu et al., 2024; Neethling, 2010; Vreÿ, 2011).

This study conducted a spatial density analysis of MP and ARS events, aiming to present the distribution patterns of areas with frequent occurrences and to project potential spread zones. Understanding the variations in spatial density based on location will facilitate the implementation of effective solutions at the correct locations, thereby yielding more effective maritime security outcomes. Different from other studies in the literature (Baird, 2012; Bueger, 2013; Okafor-Yarwood and Onuoha, 2023; Shepard and Pratson, 2020), this study takes a broader approach by analysing maritime attacks across global waters and comparing their densities over time. The study identifies current regional boundaries of attacks, providing maritime stakeholders with insights for sensitivity and situational awareness in specific regions. Additionally, the study suggests recommendations on measures and focuses on preventing attacks in emerging hotspots.

2. Historical Review of Maritime Piracy Studies

The origins of academic studies related to maritime piracy can be traced back to the early 1960s (Tarling, 1963). Piracy studies require a solid foundation of knowledge and remain an evolving and dynamic international issue that requires continuous attention. Maritime piracy is an interdisciplinary subject that spans the economy, politics and international relations, sociology, law, anthropology, and security studies. Hence, it has always held a rich and comprehensive position within academic research. Recently, there have been numerous studies conducted on this topic (Fan et al., 2024; Hao et al., 2023; Zhang et al., 2024). The research examining the issue of maritime piracy can be categorized into five main focus areas: the nature and temporal evolution of piracy (changes and developments) (He et al., 2023; Tumbarska, 2023), the investigation of the causes of piracy and their impact (Desai and Shambaugh, 2021; Phayal et al., 2024), the analysis of the effectiveness of preventive strategies against piracy (Fan et al., 2024; Zhang et al., 2024), the analysis of consequences and risks associated with piracy (Burlando et al., 2015; Nwokedi et al., 2022), and the spatial, temporal, and spatiotemporal pattern-based analysis and risk assessment (Li and Yang, 2023; Liu et al., 2021). Table 1 presents a summary and findings of the reviewed maritime piracy studies.

Table 1. Summary of the reviewed maritime piracy studies

Nature and temporal evolution of piracy: Several studies have analysed the evolution of piracy and changing nature of attacks over time using quantitative data. Tumbarska (2023) conducted a trend analysis of the 15-year period from 2008 to 2022, dividing it into three phases. The study argued that piracy and armed robbery attacks followed a fluctuating pattern, with attacks shifting from international waters to ports and territorial waters. He et al. (2023) examined 8,000 incidents that occurred between 2006 and 2021, noting that the risk of piracy

changes dynamically over time and is influenced by political situations and anti-piracy measures. Colás and Mabee (2010) and Heller-Roazen (2009) offered a historical perspective on piracy by tracing international efforts aimed at reducing its prevalence and evolution.

Examining the causes of piracy and their impact: Factors such as favourable geography, political instability and civil war, other illegal maritime crimes (Illegal, Unreported, and Unregulated (IUU) fishing, maritime terrorism, etc.), and economic conditions have been studied to understand the evolving nature of maritime piracy. Desai and Shambaugh (2021) conducted a spatial analysis exploring the global impact of IUU fishing on maritime piracy. The study analysed geo-referenced data on piracy incidents from 2005 to 2014, focusing on how destructive fishing practices, such as high bycatch and habitat destruction, contribute to piracy. The study revealed that IUU fishing activities, particularly those involving high bycatch and habitat degradation, significantly increase piracy risks, especially in regions with fragile governance. In contrast, Phayal et al. (2024) argued that contrary to the common belief that local fishers turn to piracy when foreign fishing vessels deplete resources, piracy increases when illegal fishing is restricted. Hastings, (2009) and Murphy, (2013) examined the sociopolitical and economic motivations behind piracy, as well as its organizational structure.

Analysis of the effectiveness of preventive and defensive strategies against piracy: Identifying effective intervention and preventive measures against piracy attacks, as well as analysing their impact, has been a key area of focus. These studies aim to assess the success of various strategies in mitigating piracy and ensuring maritime security. Bryant et al., (2014) studied the impact of countermeasures on maritime piracy attacks. The study analysed 452 maritime piracy incidents recorded in the IMB database between 2010 and 2011 using a conjunctive analysis method. The results showed that navigation watches and advanced lookout, along with at least two protective measures (evasive manoeuvres, alarms, onboard protection, physical barriers, etc.), dramatically reduced the occurrence of maritime piracy

incidents. Hao et al. (2023) introduced a new model in their study to analyse the evolutionary patterns of piracy and predict risk levels. The insights provided by this model have contributed to improving maritime authorities' risk management and intervention strategies against piracy. Geiss and Petrig (2011) and Kraska (2011) analyzed anti-piracy strategies, discussing legal frameworks, maritime responses, and protective measures.

Analysis of the consequences and risks of piracy: While piracy is primarily carried out for economic gain, its consequences negatively impact the global economy, security, and the psychological well-being of seafarers. Piracy poses significant risks not only to economic stability but also to the safety and security of maritime operations, creating long-lasting psychological effects on those directly involved. Bensassi and Martínez-Zarzoso, (2012) examined the economic impact of maritime piracy on maritime trade utilizing the gravity model technique in their study. The study concluded that not all types of violence against ships affect international maritime trade, but rather only very violent hijacking incidents can have an impact on international trade. Additionally, according to the results of the model they used, they found that the cost of maritime piracy to international trade is $25 billion annually. Nwokedi et al., (2022) conducted a probability analysis of maritime piracy and its implications for maritime security governance. The study concluded that certain ship types, particularly chemical and product tankers, are more prone to pirate attacks, and it emphasized the need for targeted maritime security governance strategies to mitigate the risks in high-probability regions and ship types.

Spatial, temporal, and spatiotemporal pattern-based analysis and risk assessment: In recent years, numerous studies have focused on the spatial, temporal, and spatiotemporal patterns of piracy attacks to conduct risk assessments. These analyses help identify trends and predict potential future risks, providing valuable insights for improving maritime security strategies. Jin et al., (2019) studied pirate attacks in the Strait of Malacca between 1994 and

2017 and proposed a model for assessing the risk to vessels. They compiled a total of 7,159 attack data from the GISIS database. The results indicated that the most at-risk vessels were small and open-registry vessels. Furthermore, they found that the likelihood of successful attacks increased during nighttime in territorial waters and port areas. They emphasized that passive measures could reduce attacks by 10%, while active measures could reduce them by 70-80%. Chen et al., (2023a) in their study conducted a review of 3,685 piracy incidents between July 1994 and December 2019. Focusing on five types of vessels, the study used GIS to analyse the spatiotemporal distribution of these incidents. The study found that piracy incidents tend to cluster in areas with economic depression, high unemployment, and social unrest. Notable hotspots included the waters off Somalia, the Malacca Strait, the Philippines, the Bay of Bengal, the Gulf of Guinea, and the northwest coast of South America.

Based on the literature, the primary factors contributing to the occurrence of maritime piracy include geographic conditions, the proximity of countries with differing economic and political structures, civil war, political instability, the absence of a functioning government, weak legal enforcement mechanisms, cultural acceptance, maritime insecurity, and weakness of the economy (Bueger, 2015; Bueger and Stockbruegger, 2022, 2024; Triantafillou et al., 2023). The geographical structures of countries and continents are significant factors influencing piracy attacks. The proximity of countries with different economic and political systems within the same region creates opportunities for piracy activities. Southeast Asia serves as an excellent example of this. The diverse political and economic structures of the countries in the region provide pirates with the opportunity to expand their operations across peninsulas and archipelagos (Forster, 2014; Hastings, 2009). One of the factors that motivates people to engage in armed robbery and piracy at sea is the absence of a functional, well-functioning state. Evidence suggests that local government officials have been involved in piracy operations in Southeast Asia (Phayal et al., 2022; Stach, 2017; Hastings, 2009). Piracy attacks driven by civil

war, political instability, discrimination, and chaos are often concentrated in the African region, particularly in Somalia. The lack of an effective government in Somalia has not only created opportunities for piracy but has also transformed piracy into a form of organized crime (Triantafillou et al., 2023; Neethling, 2010; Vreÿ, 2009). The Asian economic crisis severely impacted the financial situation of millions of Somali villagers who rely on regional fishing for their livelihoods. In this context, the appeal of quick cash from piracy became highly attractive to those facing economic hardship (Otto and Jernberg, 2020; Young, 2007).

The types of piracy incidents occurring in Southeast Asia can be categorized into at least three types. The first category consists of small-scale thefts and attacks that typically occur when a ship is anchored or berthed, often in ports with relatively weak security procedures. The second category involves the robbery of ships in territorial or international waters. These types of attacks are more common in Southeast Asia than the first category. Such attacks are often carried out with heavy weaponry and involve well-organized groups. The third category of attacks in Southeast Asia involves the hijacking of ships and the seizure of their cargo. In contrast, in East African waters, the most frequent type of attack is the hijacking of ships and personnel for ransom. The unfortunate reality in East Africa is that almost every hijacked ship is towed to a port and held there for months while waiting for a ransom (Otto and Jernberg, 2020; Chalk and Hansen, 2012). For this reason, globally, especially in East and West Africa, incidents of hijacking ships and personnel for ransom are more common than seizing ships and cargo. West Africa, particularly the Gulf of Guinea, is currently one of the regions where the most violent forms of piracy are observed. Attacks in this region typically occur while ships are at anchor, in port, or near the coast. In these attacks, the primary aim is often to loot valuable personal belongings, cash, and ship equipment from the crew. Another type of attack, increasingly common in West Africa, targets fishing vessels. Recently, pirates in the region have expanded their operations further offshore. Previously limited to looting, these attacks

have become more organized and complex, with the objective of stealing petroleum products to reintroduce them into the global market (Ehizuelen, 2023; Baldauf, 2010; Kamal-Deen, 2015; Onuoha, 2012b). The number of attacks in the Singapore and Malacca Straits has fluctuated since 1997. Following the 1997 Asian economic crisis, many turned to piracy, leading to a rise in attacks (Daxecker & Prins, 2015; Gaibulloev and Sandler, 2016). After the signing of ReCAAP (Regional Cooperation Agreement on Combating Piracy and Armed Robbery Against Ships in Asia) in 2004, the number of attacks decreased (Pristrom et al., 2016). In 2009, enhanced port security measures and enforcement actions by law enforcement agencies brought attacks down to near zero (Bensassi & Martínez-Zarzoso, 2012; Gaibulloev and Sandler, 2016).

Unlike others in the literature, this study took a holistic approach by analysing and comparing attacks in global waters from both temporal and spatial perspectives. The study identified the current regional boundaries of piracy activities and how these boundaries shifted over time. These findings can help maritime stakeholders become more aware of attacks in specific regions, enhancing their situational awareness and supporting proactive decision-making. Moreover, the study provided recommendations on which measures are effective and what to focus on to prevent attacks in new areas where attacks are intensifying, based on the results obtained. These findings aimed to offer suggestions to sovereign states and international organizations in regions where MP and ARS attacks are concentrated.

3. Methodology

This study conducted spatial density analyses of MP and ARS attacks in global waters between the periods 2010-2015 and 2016-2021. The objective of the study was to identify areas where attacks frequently occur and are likely to happen. Additionally, it aimed to examine the changes in the boundaries and densities of these hotspot areas over time, and to holistically and

regionally assess the factors contributing to these changes. The study tried to find accurate and reliable answers to several questions, such as the waters where attacks were concentrated, whether the concentration of attacks in certain locations was coincidental, and if the intensities of attacks vary regionally. The finding aimed to facilitate discussions on potential security vulnerabilities, appropriate control strategies and their regional applicability, and the socio-economic, cultural, and political reasons behind these vulnerabilities.

The data on MP and ARS activities covered in this study were collected from reports in databases of recognized industry organizations, such as the IMO's GISIS (GISIS, 2023), the International Maritime Bureau (IMB) Piracy Reporting Centre (ICC, 2023), and the ReCAAP Information Sharing Centre (ReCAAP-ISC) (ReCAAP, 2023). A database was created using Microsoft Excel, incorporating data from these reports, including vessel name, vessel type, gross tonnage, position of attack, date and time of attack, waters where the attack occurred, condition of the vessel during the attack, type of attack, outcome of the attack, and any loss of life or property during the attack. The study includes data on a total of 3,241 attacks on vessels, including 2,182 incidents between 2010-2015 and 1,059 incidents between 2016-2021. The vessels affected include tankers, yachts, fishing vessels, container vessels, bulk carriers, general cargo vessels, passenger vessels, Ro-Ro vessels, refrigerated vessels, and naval vessels. The study was conducted in a Geographic Information System (GIS) environment, utilizing the ArcMap 10.5 module of ArcGIS (ESRI, 2017). GIS is a powerful information management tool that can guide developments in technical, governance, social, and cultural fields (Nisanci, 2010). The GIS platform has the capability to associate numerous different databases (Anderson, 2009). In addition to spatial detail information (what, where), GIS also has the ability to hold and present non-spatial attribute information (e.g., how, why and when) in a comprehensive manner within a single database (Howari and Ghrefat, 2021). This enables the simultaneous consideration of both descriptive and spatial information using the GIS method.

Dealing with operations based on map information or with large volumes of location-linked data, and making accurate decisions based on the results of analyses, are made possible through the effective use of GIS functions. GIS is a popular method used in observing event data and analysing hotspots (Al-Aamri et al., 2021). Knowing the changes in the locations, areas, and densities of the identified hotspots will assist in determining the factors triggering the problem and in defining the locations and boundaries of the solutions to be applied.

3.1. Step by step application of the methodology

The study consists of four main steps and the flow diagram of the methodology is presented in Figure 1. In the first step, the data has been collected by beginning with obtaining data on attacks in all waters, including the spatial information of these incidents. The collected data may include some information gaps (e.g., incident's geographical location, ship's name ang ship's type), as well as duplications, therefore the dataset would need to be processed and cleaned to ensure accuracy, completeness and readiness for the analysis. The processed data were then transferred onto a world map as point locations using GIS software. Each incident was mapped individually, providing a visual representation of the spatial distribution of the attacks.

Figure 1. Flow chart of the methodology followed in the study

In the second step a suitable hotspot analysis and density mapping method is selected. Among three different types of hotspot analyses in the GIS environment examined are Moran's I (Global), Getis-Ord General G (Global), and Kernel Density Analysis (KDA). It was decided to proceed with the analysis of attacks using KDA due to its wide application and focused approach (Duong, 2007; Hart and Zandbergen, 2014; Yildiz et al., 2022b).

The Gi* statistical method was designed by Getis and Ord to identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots). The Gi* statistic is a local Spatial Autocorrelation (SA) index (Srikanth and Srikanth, 2020). This

method is suitable for distinguishing clustering patterns of high or low densities (Manepalli et al., 2011). Specifically, for a point to be considered a hot spot, it must not only have a high value but also be surrounded by other points with high values. The method compares the sum of the values of a point and its neighbours with the sum of all points in the dataset. If the local sum is significantly higher than the average sum, the point receives a high z-score, indicating that the clustering of high values is statistically significant or not (Liang et al., 2024).

While Hot Spot Analysis (Getis-Ord Gi*) provides statistical significance of hot spots based on the Gi* statistic, KDE (Kernel Density Estimation) offers a visual representation of these hot spots (Srikanth and Srikanth, 2020). The Ansel's Local Moran's Index is another tool that examines spatial autocorrelation and identifies areas of similar density. It statistically determines the distribution patterns of hot spots (clusters, outliers, etc.) (Liang et al., 2024). Moran's Index is a crucial spatial statistical measure used to detect the presence or absence of spatial autocorrelation, guiding the selection of spatial statistical methods. However, Moran's Index is primarily a statistical measure rather than a mathematical model (Chen et al., 2023b). Specifically, the Local Moran's I statistic is an effective tool for determining whether a particular event's location is statistically part of a cluster or an outlier. It is calculated using a formula that considers the spatial relationship between each observation and its neighbours (Le et al., 2022).

The KDE algorithm has demonstrated its effectiveness in identifying and visualizing hazardous locations in various studies (Erdogan et al., 2008; Le et al., 2022). Compared to other clustering techniques like K-means, K-medoids, Clustering Using Representatives (CURE), Balanced Iterative Reducing and Clustering using Hierarchies (BIRCH), Statistical Information Grid (STING), Clustering in Quest (CLIQUE), Density-Based Spatial Clustering of Applications with Noise (DBSCAN), and Ordering Points to Identify the Clustering Structure (OPTICS), the KDE algorithm offers several distinct advantages (Han et al., 2022).

The first advantage is its ability to help determine the spread tendency of a hazard's (or attack's) risk level. The spread of the hazard level can be defined as the area near the identified hot spot, which represents a region where the likelihood of an accident (or attack) occurring may increase due to spatial relationships. When these spread tendencies are analysed in relation to both spatial and temporal factors that trigger MP and ARS attacks, or the measures taken against them, it allows for more meaningful predictions regarding the causes and consequences of hazard spread tendencies (e.g., geographical conditions, seasonal conditions, war, pandemics, economic crises, social and cultural conditions, naval forces, BMP 5, satellites, and drones). This is a significant advantage for users performing spatial density analysis.

Secondly, KDE applies a common and standardized spatial analysis unit (cellular pixel and bandwidth) across the entire area, making it easier to compare and classify different parts of the region. In this study, the densities of attacks occurring in the world's waters were easily classified and compared using this feature of the KDE method (Figures 3 and 4). KDE proved to be ideal for classifying and comparing the densities of attacks both spatially and temporally for the purposes of the study.

Thirdly, the KDE analysis process effectively identifies and visualizes areas with high accident (or attack) density (O'Sullivan and Unwin, 2010). KDE enabled the clear visualization of areas with a high concentration of attacks on the world map. One of the study's objectives was to clearly visualize the boundaries of areas with high, medium, and low attack frequencies on the map, making this method the preferred choice.

In the third step, spatial density analysis of point distributions was conducted using the KDA method. KDA is a popular method used to visualize the distribution of data (Duong, 2007). Studies conducted with KDA enable the implementation of effective solutions at the correct locations, thus yielding more efficient results (Hart and Zandbergen, 2014).

KDA is an important method used in mapping the spatial density models of events (points). In the KDA method, the study area is divided into a predetermined number of cells. The KDA method draws a circle around each point and applies the mathematical equation to the entire area from the point's location to the end point of the circle (Anderson, 2009). The surface value at the point location shows the highest value, decreases as it moves away from the point towards the radius, and reaches zero at the radius value (Silverman, 1986). The formulation of KDA is shown in Equation (1) (Anderson, 2009; Shi, 2010). KDA represents the density of points falling within a circle with a defined radius and the changing point density as it moves away from the centre (Figure 2) (Erdogan et al., 2008; Tağıl and Alevkayalı, 2013; Yildiz et al., 2022a). The density value calculated for each point is distributed over a sample area, and these distributions are vertically stacked to obtain combined densities. The darkest, thickest areas observed can be used to define the core area (Bolstad, 2005).

The formulation of the Kernel Density Estimator (KDE) presented below is built on using a Gaussian kernel function, which is essentially a Gaussian (normal) distribution applied to each data point in the dataset (Anderson, 2009; Okabe et al., 2009; Yildiz et al., 2022b). Kernel Function starts with a basic Gaussian function cantered at zero as follows:

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \quad (1)$$

where $K(x)$ is a function representing a probability density function (PDF) for a single data point (x) at zero, with unit variance and zero mean.

To adapt this kernel to any data point (x_i) in a dataset, the kernel needs to be centred on (x_i) rather than zero. This is done by adjusting the equation as follows:

$$K(x - x_i) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(x-x_i)^2}{2}} \quad (2)$$

where, x is the variable, and x_i is the centre of the kernel.

Then the kernel can be made wider or narrower by introducing a bandwidth parameter h, which effects the spread of the kernel:

$$K(\frac{x-x_i}{h}) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(x-x_i)^2}{2h^2}} \quad (3)$$

To ensure that the area under the kernel remains 1, it is necessary to divide it by h as follows:

$$K_h(x - x_i) = \frac{1}{h\sqrt{2\pi}} e^{-\frac{(x-x_i)^2}{2h^2}} \quad (4)$$

Finally, the above KDE equation (4) can be extended for multiple data points, i.e., for a dataset including n number of data, $X = \{x_1, x_2, x_3, \dots, x_n\}$, the KDE is formed by summing the individual kernels for each data point and then normalizing by the number of data points n as follows:

$$\hat{f}_h(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \quad (5)$$

where; $\hat{f}_h(x)$ is the Kernel density distribution function, K is the Kernel Function with symmetric probability density function and not a negative value, h is the correction parameter called search radius (bandwidth), n is the sample size, x is the Kernel Centre, x_i is the i^{th} sample, and x-x_i is the distance between the Kernel Centre and sample value.

Figure 2. Illustration of the principle of Kernel Density Analysis (Yildiz et al., 2022b)

The most crucial part of this step of the study was determining the values of the two most significant factors that influence the outcome of the KDA: the bandwidth (search radius) and the cell size (Figure 2). The choice of bandwidth affects the emergence of hotspots, for instance, increasing the bandwidth expands the influence area of hotspots (Fotheringham et al., 2000; Gatrell et al., 1996; Silverman, 1986). While a smaller bandwidth narrows down the global definition, a larger bandwidth is more suitable for global definitions (Flahaut et al., 2003). Although there are many suggested methods for selecting the bandwidth (h), there is no universally accepted method yet. Typical proposed methods include subjective selection,

selection using a standard distribution, least squares cross-validation (LSCV), biased cross-validation (BCV), the bootstrap method (B), the plug-in method, and smoothed cross-validation. According to Silverman, (1986), if the aim of the estimates is to explore data for proposing suitable hypotheses and statistical models, the bandwidth should be chosen through subjective selection. Anderson, (2009); Erdogan et al., (2008); Sandhu et al., (2016); Tağıl and Alevkayalı, (2013) used values that provides the best results through subjective selection for determining cell size and bandwidth. Subjective selection is a commonly used method in choosing cell size and bandwidth. In the study, various search radii and cell sizes were tested (10˚×10˚, 15˚×15˚, 5˚×5˚, 10˚×20˚, 7.5˚×15˚, 0.5˚×15˚, 5˚×15˚, 15˚×20˚, 0.5˚×0.5˚, 1˚×1˚, 2˚×2˚), and the two values that yielded the best results were determined through subjective selection. These two values, a search radius of 15˚ and a cell size of 15˚; and another set with a search radius of 1.5˚ and a cell size of 1.5˚, were used in the Kernel Density estimation of the study. The 15˚×15˚ value was intended to show the boundaries and densities of areas where attacks occurred and were likely to occur on a large scale (overview) for more general definitions. The 1.5˚×1.5˚ value aimed for a more detailed examination of areas where attacks occurred. Reducing the cell size from 15˚ to 1.5˚ allowed the cellular grids to shrink by 100 times. Reducing the bandwidth from 15˚ to 1.5˚ degrees narrowed down the influence areas of hotspots. Choosing a smaller search radius and cell size allows for a more detailed analysis of the studied area (Uğurlu et al., 2015; Yildiz et al., 2022b).

In the fourth step, the hotspot classification and hierarchical clustering is performed. First the 15˚ and 1.5˚ hotspots were grouped and clustered. This process adopted the hierarchical clustering approach used by Anderson, (2009). This hierarchical process enables the classification of spatial hotspots and facilitates easier interpretation. The hierarchical method consists of four tiers in total. The lowest tier represents "point accident data" falling within grid cells. Point accident data is combined to form "hotspots" in the 2nd tier. Hotspots are classified

based on process or similarity characteristics to form "clusters" which in turn come together to form "groups" in the 3rd tier (Anderson, 2009). In the hierarchical structure created in the study, the top tier defines MP and ARS events. In the second tier, MP and ARS actions are clustered into High Density Areas (HDA), Medium Density Areas (MDA), and Low Density Areas (LDA) based on their kernel densities. There are several classification methods available in GIS for density classifications, including quantiles, natural breaks, equal intervals, standard deviations, etc. (Youssef et al., 2015). The choice of classification method depends on the distribution of the data. If the data distributions are close to normal, equal interval and standard deviation classifications are more suitable; if the data distribution has a positive or negative skewness, natural breaks and quantile classifications are more appropriate (Akgun et al., 2012; Ayalew and Yamagishi, 2005; Youssef et al., 2015). The data distributions in the study show clustering in some areas, random distribution in others, and that, in some areas, the data count was negligible. Considering this data distribution model, a skewness in the distribution of data was observed. Therefore, the natural breaks classification method, used for skewed data distributions, was applied for classifying densities in this study. Hotspots were coded and color-coded according to their densities and displayed on thematic maps. Under the third tier, MP and ARS actions were classified using the natural breaks method. Erdogan, (2009); Uğurlu et al., (2015) and Yildiz et al., (2022a) noted in their studies that evaluating the numerical values resulting from KDA could be challenging, hence they considered linguistic descriptions for evaluation. Similarly, this study included linguistic descriptions in the classification of hotspot areas since interpreting numerical data could be more difficult. These areas were coded under HDA as high-high, high-medium, high-low; under MDA as medium-high, medium-medium, medium-low; and under LDA as low-high, low-medium, low-low. This hierarchical approach allows for detailed analysis and easier interpretation by categorizing the total number of events within hotspot areas at the lowest tier, tier four (Figure 3).

Figure 3. Hierarchical structure followed in the classification of hotspot areas (Anderson, 2009)

4. Results and Discussion

In the present study, the attacks between 2010-2015, in total 2,182 incidents, were concentrated in 71 hotspot areas, while the 1,059 attacks occurring between 2016-2021 were clustered in 57 hotspot areas (Figure 4 and Figure 5). In total, 65% of the attacks from 2010-2015 and 49% of those from 2016-2021 took place in the areas with the highest density, named HDA (HH, HM, HL). HDA (HH, HM, HL) were concentrated in 7 hotspot areas during 2010-2015, but this number reduced to 2 hotspot areas in the period 2016-2021. During 2010-2015, HDA were predominantly located in East Africa, West Africa, Southwest Asia, and Southeast Asia, while between 2016-2021, they were primarily in West Africa and Southeast Asia.

Figure 4. Regional-based hierarchical classification of piracy and armed robbery attacks that occurred in all world waters between 2010 and 2015

Figure 5. Regional-based hierarchical classification of piracy and armed robbery attacks that occurred in all world waters between 2016 and 2021

The 2016-2021 period saw an increase in the number of attacks in West Africa and South America, while attacks decreased in Southeast Asia, Southwest Asia, and East Africa. The decrease was so significant in East Africa that there were no longer any HDA left in the region. In West Africa and Southeast Asia, however, HDA continued to exist; the boundaries and locations of these areas changed. The areas of HDA in West Africa and Southeast Asia were halved, and their locations shifted southward in West Africa and south-westward in Southeast Asia (Figure 6 and Figure 7).

Figure 6. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2010 and 2015 (bandwidth: 15˚×15˚)

Figure 7. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2016 and 2021 (bandwidth: 15˚×15˚)

The most intense HDA, named as HH density, observed in 2 regions during 2010-2015, were not observed in any region during 2016-2021. This result indicates that no attacks in any region during 2016-2021 reached the HH density observed in the 2010-2015 period. Despite these shifts, the Singapore Strait remained as a hotspot area with the highest concentration of attacks in both periods.

In the study, each period was analysed by comparing regions within themselves (internal comparison). Spatial densities were classified, and changes in these densities were examined to determine which regions were more, or less dense. Subsequently, regions with a high frequency of incidents were compared between the two time periods, considering temporal aspects. This comparison involved identifying commonalities and differences between the periods before conducting a detailed analysis.

4.1. Maritime Piracy and Armed Robbery Incidents in Asia

In Asia, HDA were observed between 2010-2015 in the Singapore Strait, the Strait of Malacca, Malaysia (west and east coasts), and Indonesia (west and east coasts), whereas from 2016-2021, these occurrences were noted only in the Singapore Strait (east coast) and Indonesia (east coast) (Figure 6 and Figure 7). The Straits of Malacca and Singapore serve as important maritime corridors facilitating the flow of trade between Europe, the Middle East, and East Asia (Gilpin, 2009), and are considered the lifeline of international maritime commerce (Baird, 2012). Annually, at least 30% of global trade and 50% of the world's oil transit through these straits. The Strait of Malacca, located between Indonesia and Malaysia, encompasses numerous islands not under the control of the Indonesian Government and are utilized as safe havens by pirates (Martínez-Zarzoso and Bensassi, 2013). Despite the Strait of Malacca having a significantly larger area than the Singapore Strait, the incidence of piracy attacks in the Singapore Strait has been markedly higher in both periods (notably, 2.4 times higher during 2010-2015 and 3.9 times higher during 2016-2021). Consequently, contrary to

what is suggested in existing literature (Baird, 2012; Bensassi and Martínez-Zarzoso, 2012; Pristrom et al., 2016), a separate analysis of piracy attacks in the Straits of Malacca and Singapore would be more appropriate (Figure 6 and Figure 7).

In the last five-year period (2016-2021), a significant decline in piracy attacks has been observed in the Strait of Malacca. The strait has transitioned from a HDA to an MDA. While attacks in the strait occurred both within separation zones and port areas between 2010-2015, from 2016-2021, they were limited only to port areas (Figure 6 and Figure 7). Although the Straits of Singapore and Malacca were once collectively feared by mariners, it appears that the Strait of Malacca has ceased to be as daunting a region for them. The role of the Malaysian Maritime Enforcement Agency (MMEA) and the Royal Malaysian Navy (RMN) in this reduction is undeniable (Khobragade et al., 2021). Additionally, a collaborative effort currently exists between Indonesia, Malaysia, Singapore, and Thailand known as the Malacca Straits Sea Patrol (MSSP) operating over the Strait of Malacca. The MSSP consists of the "Eyes in the Sky" (EIS) combined maritime air patrols and the Intelligence Exchange Group (IEG), facilitating coordinated aerial surveillance of vessels and immediate information sharing with relevant agencies. Furthermore, the ReCAAP represents the first significant regional intergovernmental agreement aimed at combating piracy and armed robbery at sea in the region. The ReCAAP-ISC plays a central role in enhancing the circulation of information regarding piracy incidents and related maritime security threats (Khobragade et al., 2021). In summary, the overall reduction in piracy incidents in the Strait of Malacca within the Asian region has been achieved through a series of measures including coordinated patrolling, surveillance, information sharing, capacity building, establishment of control centres, and strengthening of the legal framework.

In the Singapore Strait, piracy attacks were at a higher density from 2010-2015, but decreased to a lower density between 2016-2021. Although there has been a general decline in

attacks within the Singapore Strait, this reduction has not been as significant as that observed in the Strait of Malacca. The strait has continued to be the region's area of highest density. The boundaries of HDA in the Singapore Strait have narrowed by approximately 50%, with the dense areas shifting towards the northwest of the strait's eastern corridor (Figure 8 and Figure 9). Based on the data obtained from this section of the study, seafarers using the Singapore Strait can be advised to exercise increased caution in the strait's eastern corridor. The most effective way to combat Piracy and Armed Robbery Against Ships (PARS) is to identify and eliminate the factors that trigger incidents in areas where attacks are concentrated. Leading factors triggering PARS in the Singapore Strait include the strait's susceptible geography and the maritime insecurity arising from the proximity of countries with varied economic and political structures (Hastings, 2009). Singapore, one of the world's wealthiest countries, is connected to Malaysia, by two bridges. Malaysia, in turn, is a moderately powerful state within the visual range of Indonesia, which is considered one of the weaker states globally. The region is one of the few areas worldwide that contains a complex mix of weak and strong states coexisting together. Many countries in the region experience tensions due to the ambiguity of their maritime borders (Khobragade et al., 2021). This complex political and social structure together with the geographic conditions lay the ground for pirates to execute their planned attacks. Despite these challenges, seafarers will continue to use the Singapore Strait to minimize sailing time and maximize economic gains. Without implementing additional preventive measures to eliminate the strait's triggering factors, a sustainable solution to the issue of MP and ARS cannot be achieved.

Figure 8. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2010 and 2015 (bandwidth: $1.5^{\circ} \times 1.5^{\circ}$)

Figure 9. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2016 and 2021 (bandwidth: $1.5^{\circ} \times 1.5^{\circ}$)

Despite overall declines in PARS within the Southeast Asian region, the intensity of attacks has increased in the Philippines and around Java Island in Indonesia. Notably, the South China Sea has evolved from a LDA to an MDA during the 2016-2021 period, becoming a hazardous zone for seafarers. While measures taken to ensure the security of the straits appear to have been partially effective, they have inadvertently shifted the concentration of attacks eastward.

Outside of HDA, dense areas in the Asian continent were around South Asia and Southeast Asia. In these regions, particularly around India's eastern coast and the Bay of Bengal, the intensity of attacks has decreased compared to the past. During the 2016-2021 period, the western coast of India transitioned from HDA to LDA, while its eastern coast shifted from MDA to LDA. Consequently, except for the Bay of Bengal, South Asia was predominantly covered with LDA during this period. The decline in piracy and armed robbery incidents in the Western Indian Ocean and the Bay of Aden can be significantly attributed to the effectiveness of the Djibouti Code of Conduct (2009) and the Anti-Piracy Bill (2019) (Khobragade et al., 2021; Menefee, 2020).

These developments highlight the complex dynamics of maritime security in the region, indicating that while some areas have seen improvements, others remain vulnerable to piracy and armed robbery. The legal and cooperative measures implemented, have played a crucial role in reducing piracy incidents, demonstrating the importance of regional and international collaboration in addressing maritime security threats.

4.2. Maritime Piracy and Armed Robbery Incidents in East Africa and Indian Ocean

In the African continent, areas of HDA were predominantly observed in East Africa, the Arabian Sea, and West Africa between 2010-2015, while during the period of 2016-2021, such areas were noted only in West Africa. Of all the piracy attacks occurring in global waters from

2010-2015, 31% (679 attacks) took place in East Africa and the Arabian Sea, whereas from 2016-2021, these regions accounted for only 5% (53 attacks). Particularly in the period of 2016-2021, a dramatic decrease in attacks was observed in the Gulf of Aden, the Bab-el-Mandeb Strait, the Gulf of Oman, and the Arabian Sea. The Gulf of Aden and the Bab-el-Mandeb Strait transitioned from HDA to MDA, whereas the Arabian Sea and the Gulf of Oman moved from HDA to LDA. The coastal regions of Kenya, Tanzania, and eastern Somalia shifted from MDA to LDA (Figures 4 and Figure 5). The Arabian Sea experienced the most dramatic decline among these dense areas. Alongside the reduction in the density of areas, a narrowing in their geographical boundaries was also observed (Figures 6 and Figures 7). This dramatic decrease can be attributed to a series of international measures implemented since 2008. These measures include international naval operations, legitimate self-defence measures by the maritime sector, security sector reform and infrastructure projects, global prosecution programs, and a variety of piracy awareness campaigns (Bueger, 2015).

Hopkins in 2013, the U.S. coordinator for counter-piracy efforts, attributed the decrease in regional attacks to four main factors: the arming of vessels and the proper implementation of the BMP guide, the close and effective cooperation of naval forces of countries combating piracy, the increasing willingness of countries to prosecute, and the policy of the Somali people to exclude (not tolerate) pirates (Bueger, 2015). Naval forces, have been deployed throughout the region, allowing for responses to attacks not only from the sea but also from land and air. This approach underscores the importance of international collaboration and multi-dimensional strategies in significantly reducing piracy incidents in these maritime areas.

The study conducted has observed an 89% reduction in PARS in East Africa during the 2016-2021 period. A region that once contained the most intense and broadly defined dense area in global waters has nearly transformed into an area where attacks are almost non-existent (Figure 4 and Figure 5). The issue of piracy and armed robbery in East Africa has captured the

attention of the global community, successfully rallying international powers to unite in search of a solution. In this context, PARS have opened a window of opportunity for the reorganization of maritime security management and the creation of sustainable institutions. However, this dramatic reduction, along with the opportunity it presents, could quickly disintegrate. If the solutions implemented in the wake of this gained momentum are not approached with careful consideration, or if they lack permanence, ensuring the region remains free of piracy and armed robbery would be challenging.

4.3. Maritime Piracy and Armed Robbery Incidents in West Africa

This study has identified West Africa, particularly the Gulf of Guinea, as another region where PARS are most prevalent. The Gulf of Guinea encompasses approximately 1,200 nautical miles of coastline and offshore areas stretching from Ghana to Gabon along the West African coast. This region is among the world's richest in terms of natural resources, holding 86% of Africa's oil and natural gas reserves. Its wealth of natural resources and strategic location make it a vital passage for global maritime trade and a point of interest for foreign nations (Onuoha, 2012a). However, the economic potential of the Gulf of Guinea, attributable to its rich resources and strategic position, has also attracted piracy and armed robbery issues. The study found that 13% of all piracy attacks in global waters from 2010-2015 and 32% from 2016-2021 occurred in the Gulf of Guinea. While a general decrease in attacks in global waters was observed, an increase was noted in West Africa, with attacks rising by 11% compared to the 2010-2015 period (Figure 4 and Figure 5). Despite the increase in the number of attacks, the geographical boundaries of the hotspot areas where these attacks occur have significantly narrowed. This suggests that while the area of hazard in West Africa has narrowed, the likelihood of being attacked within these new boundaries has increased.

Between 2010-2015, HDA in colours of red, orange, and yellow extended from Gabon to Sierra Leone, while during the period of 2016-2021, these areas reduced by half, shifting

eastward to Ghana and southward to Angola. A detailed examination of attack distributions (using 1.5° KDA) revealed that during 2010-2015, Togo, Benin, and Lagos, and between 2016-2021, Benin, Lagos, and the waters off Port-Harcourt of Nigeria (100-125 miles) were located within HDAs (Figure 8 and Figure 9). In both periods, attacks showed a clustering distribution in Togo, Benin, and Lagos, while a random distribution was observed off Port-Harcourt (Nigeria). From 2016-2021, the waters off Port-Harcourt (Nigeria) shifted from MDA and LDA to HDAs, whereas Togo moved from an HDA to an LDA. Consequently, while the intensity and coverage area along the coasts of Togo, Benin, and Lagos in the Gulf of Guinea have decreased, the density of Port-Harcourt (Nigeria) and Warri (Nigeria) has increased, and the area of concentration has expanded southwards. Based on these data, it can be inferred that piracy attacks in West Africa have recently started to shift towards the open seas, particularly concentrating in the southeastern part of the Gulf of Guinea. In other words, the offshore areas of the Gulf of Guinea have become more dangerous for seafarers compared to the past. Attacks occurring offshore, in open seas, or beyond a state's jurisdiction require more external support and equipment. The occurrence of attacks in international waters, surpassing port areas, anchoring areas, and even territorial waters, can indicate an escalating threat in the region.

Bueger, (2015) argued that the problem of piracy and armed robbery against vessels serves as a typical example of broader maritime security challenges and that lessons learned from East Africa and the Somali region could be applied to other areas. A characteristic of piracy is its ability to escalate rapidly, and once it does, it becomes difficult to control. Delayed measures and interventions in East Africa led to a significant decrease in attacks during the 2011-2012 period, but the world economy and maritime industry had to pay a heavy price. The increasing trend of attacks in the Gulf of Guinea and their shift towards the open sea could indicate a potential for rapid escalation similar to that in East Africa. Without early intervention

in the Gulf of Guinea, the effort and financial cost to mitigate the consequences will be significantly higher.

Liwång, (2017) argues that piracy in West Africa is more diverse, successful, and dangerous. Onuoha, (2012b) and Ukiwo, (2007) highlight that attacks in the Gulf of Guinea are carried out with advanced weapons, are more organized, and are more violent compared to other regions. The Gulf of Guinea can be described as a new hotspot area for intensified piracy activities. Attacks on vessels are conducted using fast boats, typically at night, and involve large groups (40 or more individuals). Previously, attacks were primarily aimed at robbery, but now they are more organized and complex, with the goal of stealing petroleum products to reintroduce them into the global market. It is believed that these operations are backed by powerful transnational mafias with extensive knowledge of the petroleum industry's operations. These mafias provide the pirates with the financial means and necessary information (such as vessels names, the amount of oil, and destinations) to conduct their operations (Baldauf, 2010; Kamal-Deen, 2015; Onuoha, 2012b).

Although the number of piracy incidents in the Gulf of Guinea has fluctuated over the past few decades, the region is currently experiencing an increase in these illegal activities. In addition to combating piracy, kidnapping, and robbery at sea, the region also faces challenges such as a growing population and a crisis of illegal fishing (Denton and Harris, 2021).

4.4. Maritime Piracy and Armed Robbery Incidents in Other Areas

In the northern region of South America, there has been a general increase in the number of attacks, with incidents concentrating in the north and northwest areas. Additionally, despite the absence of attacks in the Gulf of Mexico between 2010 and 2015, incidents were observed from 2016 to 2021. For both periods, it has been identified that regions including Europe, Australia, East Asia, and Antarctica experienced negligible or no issues related to piracy and maritime security threats.

In 2000, various countries joined their forces to combat piracy and ensure the stable growth of international trade by establishing relevant organizations and shipping convoys. Over time, this collaboration significantly reduced the number of piracy incidents and the risk of pirate attacks on ships in some areas (Zhang et al., 2024). The peak in attacks in 2012 in East Africa and the Indian Ocean was brought under control through the cooperation of United Nations (UN), European Union (EU) member States, and North Atlantic Treaty Organization (NATO) forces, leading to a rapid decline in such incidents. Not only did East African countries contribute to resolving the problem in the region, but non-regional countries such as China, India, France, Spain, Ukraine, and Russia also provided support (Cusumano et al., 2020; Ehiane and Uwizeyimana, 2023). In West Africa, the Gulf countries, including Nigeria, Cameroon, Togo, Benin, and Angola, are making efforts to combat this issue. Notably, Nigeria is actively engaged in the region, particularly with its naval forces (Bell et al., 2021; Ehizuelen, 2023). In the Asian region, all countries are actively combating the MP and ARS problems. Japan and Malaysia conduct joint coast guard exercises to fight piracy in Southeast Asia. Additionally, the Philippines, Indonesia, and Malaysia have shown that by enhancing information sharing and conducting joint sea and air patrols, they have reduced the overall incidents of piracy and kidnapping (Reid, 2019). These coalitions also support weak states that are insufficient in combating pirates on their own (Daxecker and Prins, 2015).

Large and mostly ungoverned maritime areas (i.e. international waters of relatively poorer States) are the ones that terrorists and pirates actively seek to exploit to achieve their land-based goals. The overlapping characteristics and notable similarities between pirates and terrorists operating at sea make it difficult to distinguish between them. Such ambiguities complicate efforts to effectively combat these threats. The main factors that differentiate these two phenomena are the motivations, methods, and objectives of the individuals carrying out the actions (Nelson, 2012). Generally, pirates are criminals who use violence for financial

gains, whereas terrorists use violence as a means to achieve a political goal. A renowned terrorism expert Hoffman (2006) notes that one of the defining characteristics of terrorism is its "inevitably political" purpose and motivation. However, terrorists may conduct maritime attacks to finance their land operations, leading some to conclude that piracy and maritime terrorism are the same (Mitchell, 2010). Despite this overlap, one is carried out solely for monetary gain, while the other is seen as a means to achieve a political goal (Mitchell, 2010). It is clear that the perpetrators of these actions have different motivations and select their targets based on different objectives (Singh, 2019). There is growing concern within the international community about the collaboration between these actors toward different goals. The land conflicts in Yemen have had a significant impact on the maritime domain (Devendra, 2018). Reports indicate that Houthi forces have seized ships belonging to countries with which they have political disputes, attacked commercial shipping with rockets from aerial drones and fast-moving boats, and mined shipping lanes in the Southern Red Sea (Williams et al., 2020). Another study shows that between January 2017 and June 2021, the Houthis carried out 24 maritime drone attacks against commercial vessels, port infrastructure, and oil production and distribution facilities in Saudi Arabia (Bueger and Stockbruegger, 2022). It is evident that these attacks were not carried out for financial gains. However, the collaboration between criminals and terrorists for different purposes creates a complex and ambiguous situation in legal, political, and social terms. Policymakers need to have a clear understanding of maritime terrorism and piracy to overcome the challenges of mitigating these threats (Nelson, 2012).

4.5. Sea Area Distribution of Maritime Piracy and Armed Robbery Incidents

When global waters were examined, it was observed that attacks occur most frequently in international waters, followed by port waters, and least often in territorial waters (Table 2). In the Americas and Asia, attacks are more common in port waters, whereas in West and East Africa, they predominantly occur in international waters. A comparison of the two time periods

reveals an increase in attacks within the territorial waters of the Americas. In this region, attacks have clustered around ports and territorial waters (possibly at anchor points). In West Africa, there has been a recent increase in attacks in international waters (a rise of 10.7%), with this increase notably clustering off the coast of Nigeria. However, no significant changes have been observed in attacks occurring in territorial waters. In East Africa, attacks in international waters have decreased dramatically, and recent attacks are now distributed almost equally across territorial waters, port waters, and international waters, forming clusters. In Asian waters, there has been a recent decline in attacks in port waters and international waters, while attacks in territorial waters have increased by 7%.

Table 2. Distribution of incidents in high density areas by region, country and sea area

5. Recommendations to Mitigate Maritime Piracy and Armed Robbery Incidents

Given the increasing complexities in maritime security, implementing effective measures to combat MP and ARS is of paramount importance. The results of this study, along with existing literature, emphasize that the most critical requirement in addressing MP and ARS incidents is the adoption of effective preventive measures (Bryant et al., 2014). The BMP guidelines recommend that measures to prevent MP and ARS should be categorized under a situational crime prevention approach. Situational crime prevention is a strategy aimed at reducing crime by making it less attractive to criminals, either by offering fewer opportunities or by making the existing environment riskier for offenders (Clarke, 1995; Eck and Clarke, 2019).

Ultimately, it is the ship's crew members who confront and deal with maritime pirates, whether before, during, or after an attack. Therefore, establishing a structured and standardized training and certification system under the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) framework for personnel working in regions with high MP and ARS activity could help reduce the frequency of these attacks.

Additionally, companies should provide detailed training for crew members before they board the ship, focusing on effective techniques and practices for responding to MP and ARS attacks. Increasing the frequency of anti-piracy drills and training on board, as well as providing seafarers with real-time regional risk maps, could further contribute to reducing attacks. High-density areas on these maps can be continuously monitored for piracy activities using satellite imagery and surveillance systems.

Moreover, with the presence of autonomous ships, the highly connected and intelligent systems they employ are becoming more vulnerable to cyberattacks, thereby increasing security risks (Zhou et al., 2021). Modern pirates closely follow industry innovations and are capable of exploiting the vulnerabilities introduced by new technologies to their advantage (e.g., rerouting ships, misleading them, or completely stopping the vessel). It is recommended that stakeholders involved in addressing this issue focus on developing remote identification systems to counteract the security risks posed by autonomous ships (Liang et al., 2024).

The BMP5 and Global Counter Piracy Guidance for Companies, Masters, and Seafarers (GCPG) manuals, which include necessary instructions and procedures for effectively combating piracy and ensuring maritime security, provide guidance to captains, companies, and seafarers on what actions to take both before and after an attack occurs. These guidelines, endorsed by leading industry organizations, are considered to have contributed to the reduction of piracy incidents (Cusumano and Ruzza, 2020; Simonds, 2022).

Before entering high-risk areas known for frequent pirate attacks, captains should establish communication with the relevant reporting centres responsible for the security of the area and exchange necessary information. This step ensures that assistance can be provided as quickly as possible in the event of an attack. Effective watchkeeping and advanced lookout procedures are among the most crucial measures in combating piracy (Psarros et al., 2011). Additional measures such as extra watchkeepers, shorter watch periods, advanced night-vision

binoculars, decoy mannequins, and enhanced radar monitoring can support these efforts (Gong et al., 2023). Every captain should equip their ship to prevent unauthorized access to the bridge, living quarters, and engine room (using barbed wire, water and foam jets, closed and locked hatches, chained barriers, sandbags, film-coated windows, decoy mannequins, and armed or unarmed security personnel) (Bryant et al., 2014; Cusumano et al., 2020; Pristrom et al., 2016).

Different stakeholders in maritime transportation require clear guidance on piracy trends to plan safe, economical, and suitable routes, thereby reducing the risk of piracy and ensuring navigational safety (Boshoff and Sefatsa, 2019; Jin et al., 2019). The thematic maps developed in this study provide clear boundaries to assist stakeholders in making necessary route planning decisions. On the other hand, force majeure events occurring worldwide also have a close impact on MP and ARS. The recent COVID-19 pandemic, while reducing land-based illegal criminal activities (Estévez-Soto, 2021; Payne et al., 2020), increased maritime piracy activities (Gold et al., 2023; Sackey et al., 2022). The strict restriction measures of the pandemic paralyzed many sectors of countries and negatively affected the global economy. These deepening economic impacts made it difficult for individuals to access legal livelihoods (such as the fishing industry), thus facilitating a turn to illegal activities like piracy (Daxecker and Prins, 2015; Gold et al., 2023).

Association of Southeast Asian Nations (ASEAN) countries, which are heavily dependent on the blue economy, were more severely affected by this health crisis, experiencing dramatic increases in overall growth decline, trade volume reductions, and unemployment (Chong et al., 2021). Piracy incidents have increased in the coastal waters of countries like Bangladesh, Indonesia, and Malaysia (Anele, 2023; Gold et al., 2023). As a result, it is clear that large-scale health and economic crises can have significant impacts on illegal criminal activities such as maritime piracy. Governments need to carefully evaluate whether the policies they implement to combat such crises are sufficient in mitigating economic hardships and

reducing societal grievances. In other words, measures taken to contain the pandemic should not trigger illegal criminal activities.

Although piracy incidents have declined in recent years, job losses and increasing poverty resulting from the COVID-19 pandemic (Li and Yang, 2023; Seidl et al., 2023) could lead to a resurgence in maritime piracy. Therefore, a better understanding of the characteristics of maritime piracy is necessary to propose appropriate measures to enhance maritime security and reduce the impact of piracy on the maritime industry (Fan et al., 2023; Liu and Luo, 2023). The experiences during the pandemic offer important lessons for predicting and preventing the impacts of similar crises on criminal activities in the future, providing a window of opportunity for relevant stakeholders.

6. Conclusions

MP and ARS are among the most significant threats to commercial vessels navigating the world's oceans. This issue arises from failures in political, social, and legal areas of states, as well as economic ambitions, and is further triggered by gaps in international law, enforcement mechanisms, and the increase in global trade volume. Pirates attack vessels primarily for financial gains, but the impacts of these attacks extend beyond the targeted country, affecting regional and even international domains. This cycle is not a problem that can be resolved by simply addressing the social, political, or economic conditions of a single region or country. Additionally, with the continuous advancement and change in technology, maritime traffic is constantly increasing, and pirates are continually evolving their methods. While it may not be possible to completely eliminate piracy and armed robbery at sea, understanding the location-based changes in these attacks can lead to the application of effective solutions in the right places, thereby achieving more effective outcomes.

This study conducted a spatial density analysis of piracy and armed robbery incidents in all the world's waters for the periods 2010-2015 and 2016-2021 and compared the two periods.

Through spatial density analysis, the study identified hotspot areas (potential attack areas) based on the locations of attacks, highlighting areas of concentration and trends of spread. This research is the first to comprehensively address and analyse the incidents of piracy and armed robbery at sea across the globe through spatial density analysis.

In the study, when comparing two periods, a significant reduction by half in the number of attacks worldwide was observed. Additionally, a similar reduction in the size of the areas most affected by these incidents was noted. This reflects a positive outcome indicating a growing awareness of MP and ARS issues on both national and international platforms, demonstrating the effectiveness of international and regional collaborations. The study found that factors such as favourable geography, weak legal enforcement, maritime insecurity, economic deterioration, and cultural acceptance have been triggering these MP and ARS attacks. Despite the difficulty of completely eliminating these triggers, preventative and protective measures have begun to reduce piracy activities in many regions, including the Strait of Malacca, off the coast of Somalia, the Gulf of Aden, and the Arabian Sea. However, as long as the root causes are not fully addressed, efforts to combat MP and ARS will always require resources and financial investment. Therefore, maritime insecurity should be recognized as an issue requiring continuous international attention and action.

While a general decrease in MP and ARS attacks was observed worldwide, increases were noted in Western Africa and South America. In Western Africa, not only did the intensity of attacks increase, but there was also a tendency for attacks to shift towards the southeast off the coast of the Gulf of Guinea. Moreover, due to the violence and fear in the Gulf of Guinea, vessels operators are not reporting incidents to authorities, leading to data inaccuracies (Okafor-Yarwood et al., 2024). This situation clearly indicates that the measures taken in the Gulf of Guinea are insufficient or ineffective. If immediate action is not taken to address the increase in Western Africa, an accelerating rise in regional attacks would not be surprising.

Delays in intervention and preventative measures will lead to extra costs and financial burdens for national and international organizations involved.

The study observed the most dramatic decrease in MP and ARS in the East African region. This reduction has been so significant with only 53 attacks reported in the region over the last five years (2016-2021). This decrease has been achieved through international and regional collaborations in the area. However, the underlying factors that trigger these maritime security threats continue to persist in the region. Any minor disruption in the implementation of measures or political conflicts between countries could potentially reignite the MP and ARS issues in East Africa.

Unlike other studies, this study provides original insights by creating maps that show the boundaries and intensities of attacks, allowing for the implementation of effective solutions in precise locations for better outcomes. Through MP and ARS density maps, the research identifies vulnerable and secure areas in global waters, offering recommendations for industry stakeholders to focus on these regions. Additionally, knowing the boundaries of these hotspots helps authorities accurately time their anti-piracy drills and preparations, enhancing their defensive measures.

Future research could benefit from a more detailed temporal analysis, using different methodological approaches (i.e., incorporating time-series analysis) to capture seasonal (weather and sea state) or short-term variations in incident occurrences. This could provide additional insights into the dynamics of piracy and armed robbery incidents and inform policy and security strategy adjustments.

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Table 1. Summary of the reviewed maritime piracy studies

Author (Year)	Contribution	Dataset	Method	Findings
Tarling (1963)	Origins of academic studies on maritime piracy.	Historical records and qualitative analysis.	Descriptive and historical analysis.	Maritime piracy is a significant issue that needs to be studied and addressed.
Bensassi and Martínez-Zarzoso (2012)	Economic impact analysis using the gravity model.	International trade data and piracy incident reports.	Gravity model technique.	Severe hijacking incidents impact trade, costing $24.5 billion annually.
Bryant et al. (2014)	Study on the effectiveness of piracy countermeasures.	IMB database (452 piracy incidents, 2010-2011).	Conjunctive analysis method.	Protective measures like navigation watches reduce piracy incidents.
Kamal-Deen (2015)	Evolution of piracy in the Gulf of Guinea and response strategies.	IMO and IMB databases (piracy incidents 2005-2013).	Risk assessment and categorization.	Highlighted the growing threat and recommended establishing a security fund under the IMO.
Burlando et al. (2015)	Trade consequences of Somali piracy.	Global panel data on trade volumes and piracy attacks (2000-2010).	Augmented gravity model.	Somali piracy reduced bulk commodity trade by 4.1% annually, impacting 70% of global trade costs.
Pristrom et al. (2016)	Development of a predictive model for piracy attacks using Bayesian logic.	GISIS data and expert insights.	Bayesian logic and security analysis.	The model predicts piracy likelihood based on vessel and environmental factors.
Jacobsen and Larsen (2019)	Study of the constitutive effects of maritime security interventions.	Fieldwork and desk research on piracy off the Horn of Africa.	Descriptive and content analysis.	Counter-piracy interventions have shaped new intervention actors and alliances in maritime security.
Jin et al. (2019)	Risk assessment model for piracy in the Strait of Malacca.	GISIS data (7,159 incidents, 1994-2017).	Binary logistic regression.	Identified risk factors for vessels; emphasized passive and active defence measures.
Desai and Shambaugh (2021)	Impact of illegal fishing on maritime piracy.	Geo-referenced data on piracy and fishing practices (2005-2014).	Spatial analysis.	Illegal, unreported, and unregulated (IUU) fishing exacerbates piracy, especially in high-bycatch areas.
Liu et al. (2021)	Piracy risk assessment using empirical models.	IMO, IMF, WRI, and other international datasets.	Bayesian network and cloud model theory.	Developed a quantitative framework to assess piracy risk by integrating hazard, vulnerability, and antirisk properties.
Nwokedi et al. (2022)	Probability analysis of maritime piracy and implications for security governance.	IMB reports (piracy incidents from 2011-2020).	Empirical probability statistical method.	Southeast Asian and African waters have the highest probabilities of pirate attacks; trauma is the most common effect on crew members.

Author (Year)	Contribution	Dataset	Method	Findings
Fan et al. (2023)	Spatial patterns and characteristics of global piracy analysed using GIS methods.	PAR module of GISIS (3675 incidents from the 2010-2022 period).	Kernel density estimation (KDE), k-means clustering, and buffer analysis.	Identified piracy hotspots in the Gulf of Guinea, East Africa, Southeast Asia, and South America, with most incidents occurring within 40 km of the coast.
Li and Yang (2023)	Overview of interdisciplinary studies on maritime piracy.	Literature review and meta-analysis.	Qualitative synthesis.	Confirmed the interdisciplinary nature and evolving dynamics of piracy studies.
Chen et al. (2023)	GIS-based investigation of spatiotemporal characteristics of pirate attacks.	Data on 3,685 incidents (1994-2019).	GIS, Kernel Density Estimation (KDE).	Identified clustering patterns of piracy; key hotspots include waters off Somalia, Malacca Strait, and Gulf of Guinea. Recommended measures to enhance awareness.
Hao et al. (2023)	A new probabilistic linguistic Markov model combined with fuzzy inference to analyse evolving patterns of piracy and predict risk levels.	Reports from (IMB) and other global maritime databases	Probabilistic linguistic Bayesian network	Proposed model is quite effective in predicting the dynamic evolution of piracy risk and is more successful in managing uncertainties than traditional risk assessment models.
He et al. (2023)	A clearer understanding of the dynamic nature of piracy and its impact on maritime transport.	Data from 2006 to 2021, analysing over 8000 piracy incidents.	Sentiment analysis, combination of risk analysis and text mining methods, Spatial analysis	The severity and nature of piracy vary from region to region and there is a need for adaptive risk management strategies for shipping.
Li and Yang (2023)	Spatio-temporal pattern mining in maritime piracy incidents.	Combined data from three major databases.	FADTW, DBSCAN.	Developed a holistic framework for analysing piracy; identified temporal and spatial patterns to aid in anti-piracy strategy development.
Tumbarska, (2023)	Contribution to the understanding of how maritime piracy and armed robbery have evolved	Annual reports from the IMB (2008-2022).	Trend analysis.	Findings reveal a fluctuating pattern of piracy and armed robbery incidents.
Fan et al. (2024)	An innovative methodology has been developed to investigate the effectiveness of naval escorts in preventing illegal piracy attacks.	Data set compiled from multiple databases (2000-2019).	Tree-Augmented Naive (TAN) Bayesian networks	Under external pressures, pirates develop different strategies and there are geographical shifts in pirate areas.

Author (Year)	Contribution	Dataset	Method	Findings
Liang et al. (2024)	Examination of the root causes and organizational aspects of piracy.	Case studies and organizational analysis.	Comparative analysis and case studies.	Explored the root causes and organization of piracy activities.
Liang et al. (2024)	Spatial temporal patterns analysis of global piracy incidents.	Data on 3,716 incidents (2010-2021).	Kernel Density, Getis-Ord Gi*,Moran's I.	Identified trends in piracy risk levels; highlighted the need for international cooperation to manage piracy effectively.
Phayal et al. (2024)	A novel perspective on the causal relationship between illegal fishing and piracy.	Data from the Indonesian Exclusive Economic Zone (EEZ) (1990-2017) including information on vessel traffic, illegal fishing incidents and piracy attacks.	Spatial analysis.	No significant relationship was found between legal fishing and piracy, indicating that the effect of environmental depletion on these crimes is limited.
Zhang et al. (2024)	Quantitative analysis of maritime piracy.	Data on 4,033 incidents (2006-2021) from GISIS database.	KDE, K-Clustering, Kruskal-Wallis test.	Analysed regional differences in piracy incidents; identified the Gulf of Guinea as a high-risk area, provided insights for reducing maritime piracy risks.

Table 2. Distribution of incidents in high density areas by region, country and sea area

Region	Country or Hotspot Area	Distribution Pattern	Incident Sea Area	Number of Incidents	
				2010-2015	2016-2021
Asia	Singapore Strait, Indonesia	Clustering	Port Waters	478	224
	Indonesia (Jakarta)	Clustering			
	Indonesia (Sumatra)	Clustering			
	Malaysia, Indonesia (Kalimantan)	Clustering / Random			
	Bangladesh (Chittagong)	Clustering			
	Bangladesh, India (Bay of Bengal)	Clustering	Territorial Waters	333	207
	Indonesia, Malacca Strait	Random			
	Indonesia (Northern Coast of Sumatra)	Clustering			
	Vietnam	Clustering and Random			
	Malaysia, Indonesia, Makassar Strait	Clustering			
	Philippines (Philippine Sea)	Clustering	International Waters	148	73
Central America	Caribbean	Random	Port Waters	97	76
South America	Venezuela	Clustering	Territorial Waters	19	53
South America	Ecuador, Colombia, Brazil	Random	International Waters	3	2
West Africa	Gulf of Guinea (Togo, Benin, Nigeria, Ivory Coast)	Clustering	Port Waters	111	97

	Nigeria, Cameroon (East and Southwest Coasts)	Clustering	Territorial Waters	79	78
	Gulf of Guinea (Togo, Benin, Nigeria, Ivory Coast)	Clustering	International Waters	120	171
East Africa	Gulf of Aden, Yemen (Aden)	Clustering	Port Waters	60	28
	Southern Red Sea (Yemen, Eritrea)	Clustering	Territorial Waters	65	22
	Kenya, East of Tanzania	Random			
	Oman	Random	International Waters	633	28
	Somalia, Kenya	Random			
	Kenya, East of Tanzania	Random			

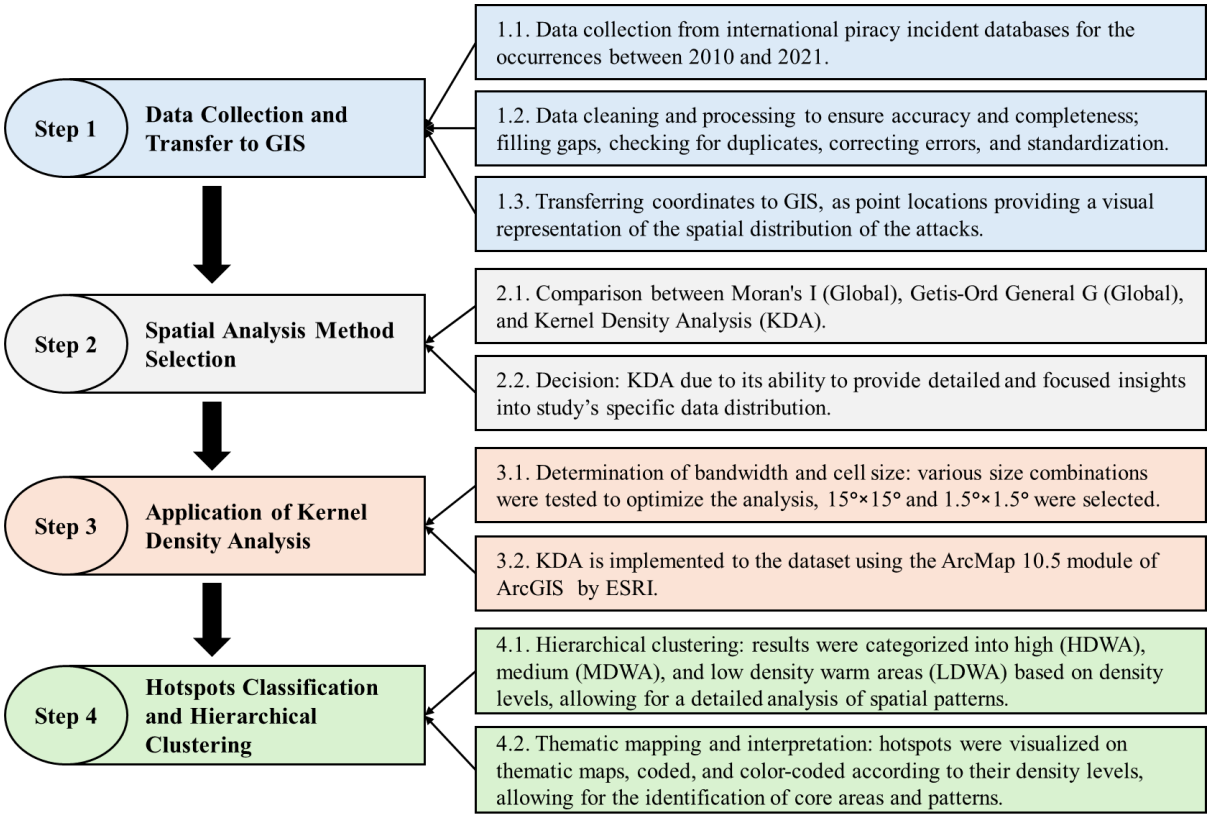
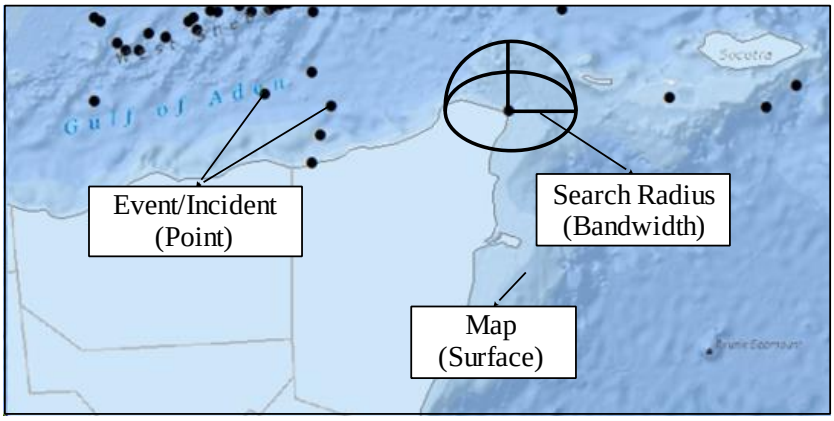
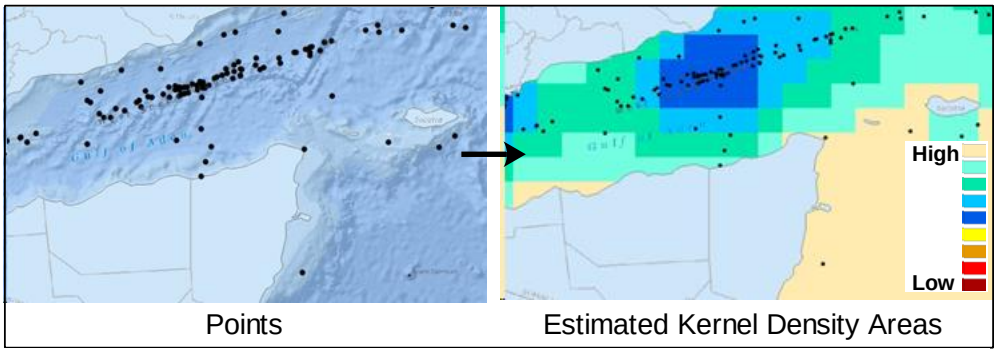


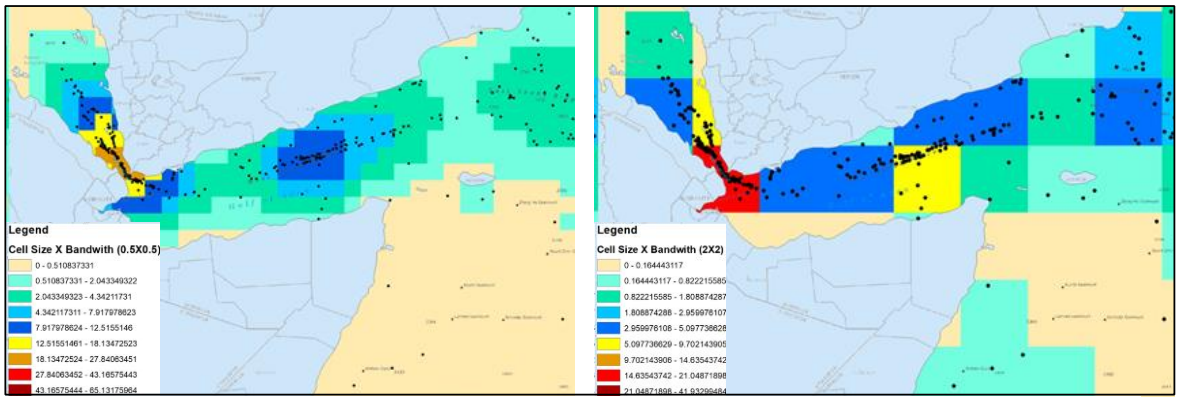
Figure 1. Flow chart of the methodology followed in the study



2a. Kernel search radius (bandwidth) of a point

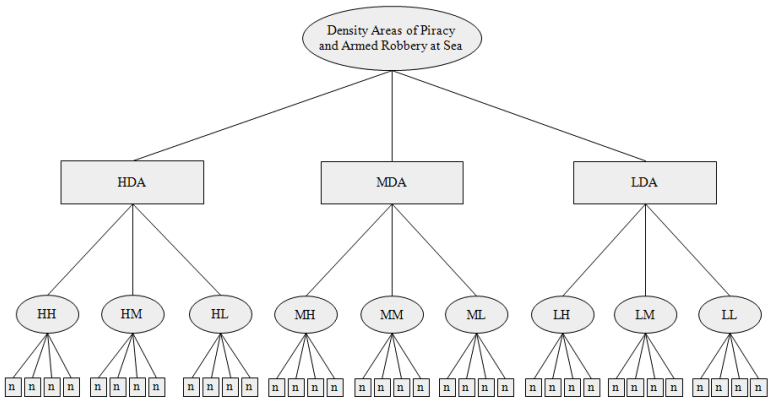


2b. Conversion of point data map to Kernel density map



2c. Difference between choosing 0.5° and 2° Kernel bandwidth

Figure 2. Illustration of the principle of Kernel Density Analysis (Yildiz et al., 2022b)



Abbreviation	Full Form
HDA	High Density Area
MDA	Medium Density Area
LDA	Low Density Area
HH	High-High Density
HM	High-Medium Density
HL	High-Low Density
MH	Medium-High Density
MM	Medium-Medium Density
ML	Medium-Low Density
LH	Low-High Density
LM	Low-Medium Density
LL	Low-Low Density
n	Number of incidents

Figure 3. Hierarchical structure followed in the classification of hotspot areas (Anderson, 2009)

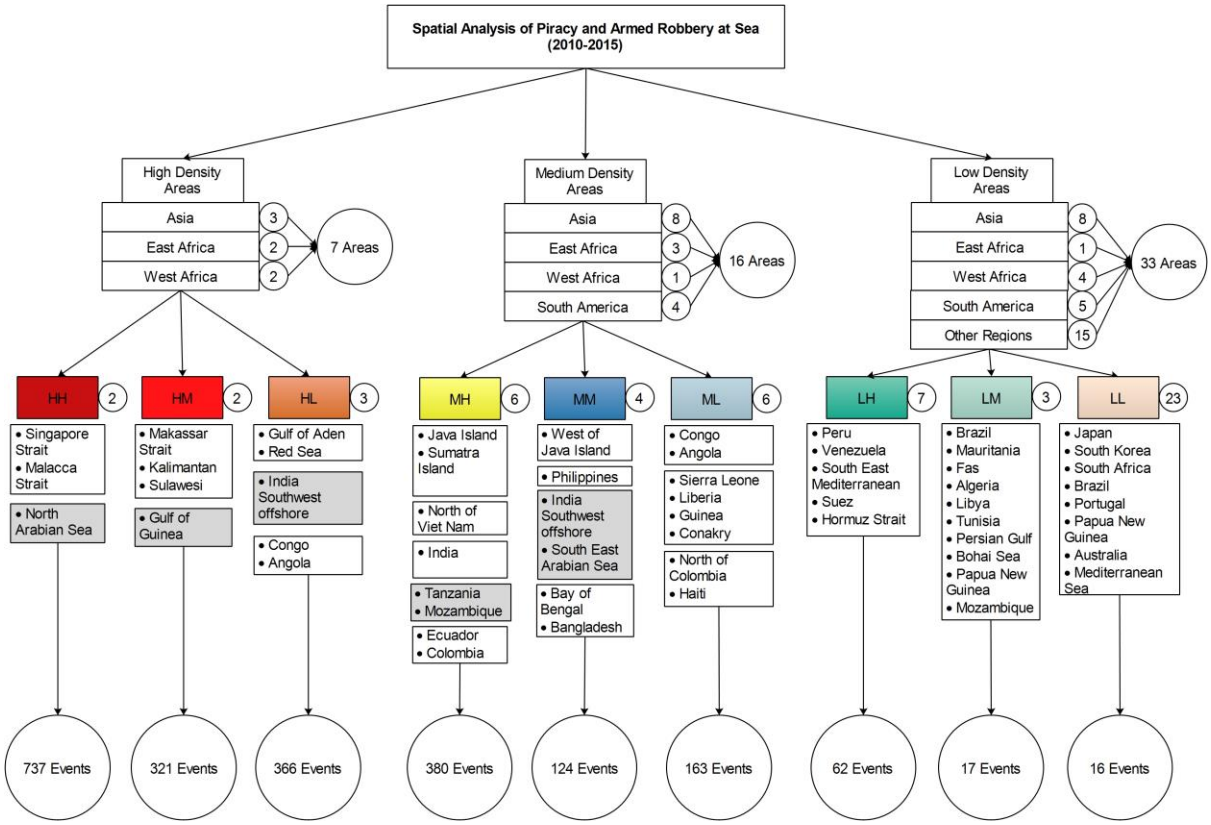


Figure 4. Regional-based hierarchical classification of piracy and armed robbery attacks that occurred in all world waters between 2010 and 2015

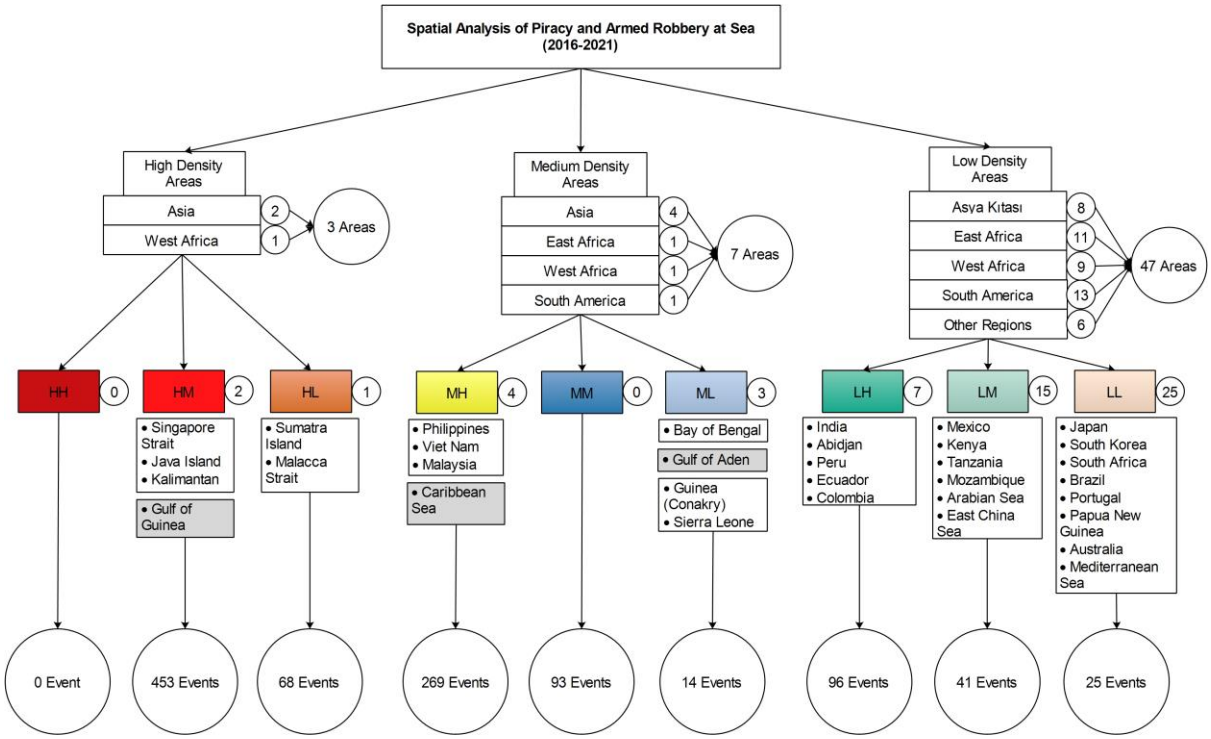


Figure 5. Regional-based hierarchical classification of piracy and armed robbery attacks that occurred in all world waters between 2016 and 2021

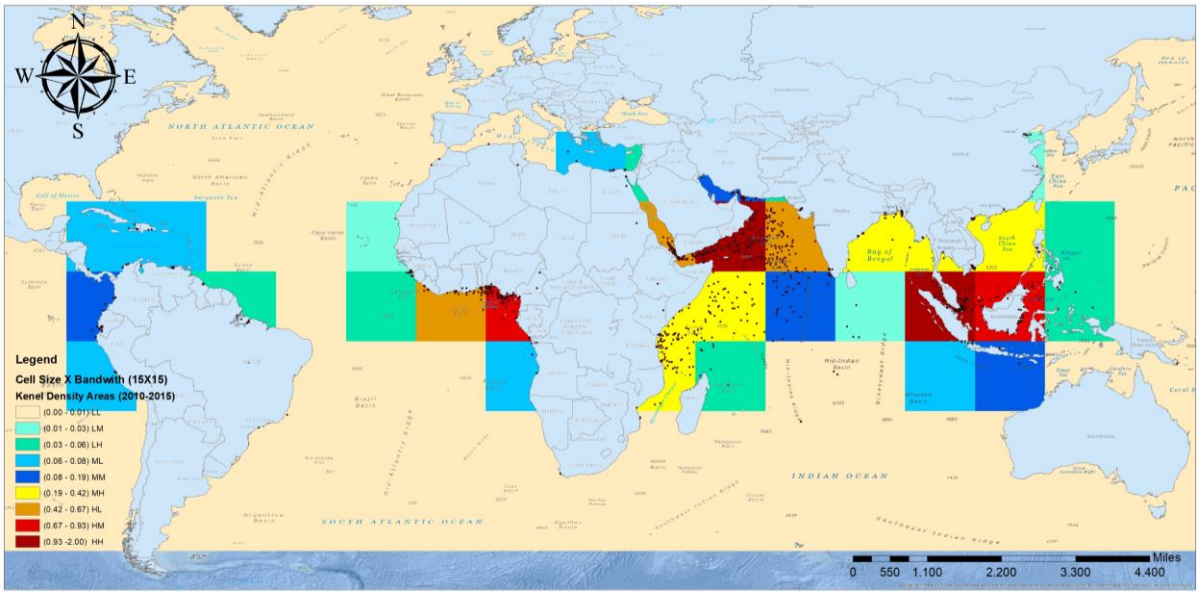


Figure 6. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2010 and 2015 (bandwidth: 15˚×15˚)

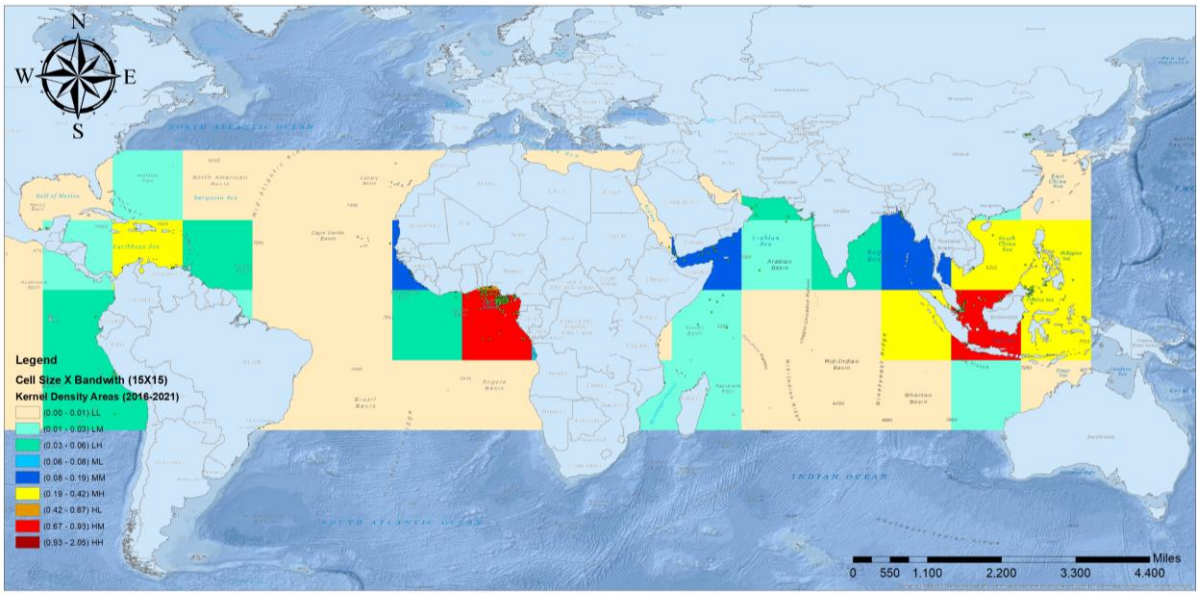
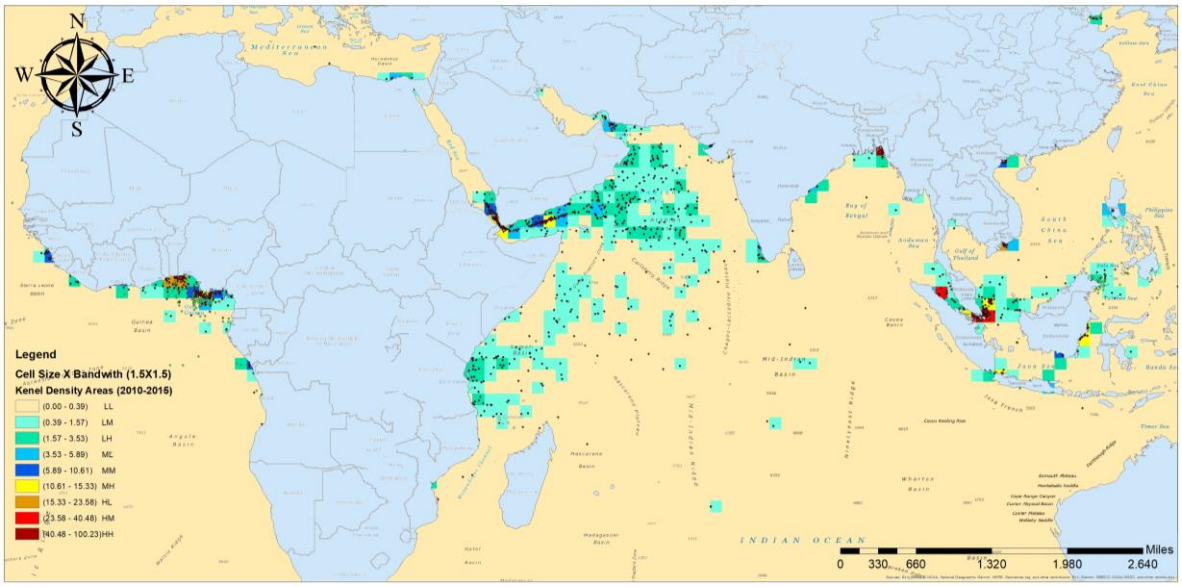
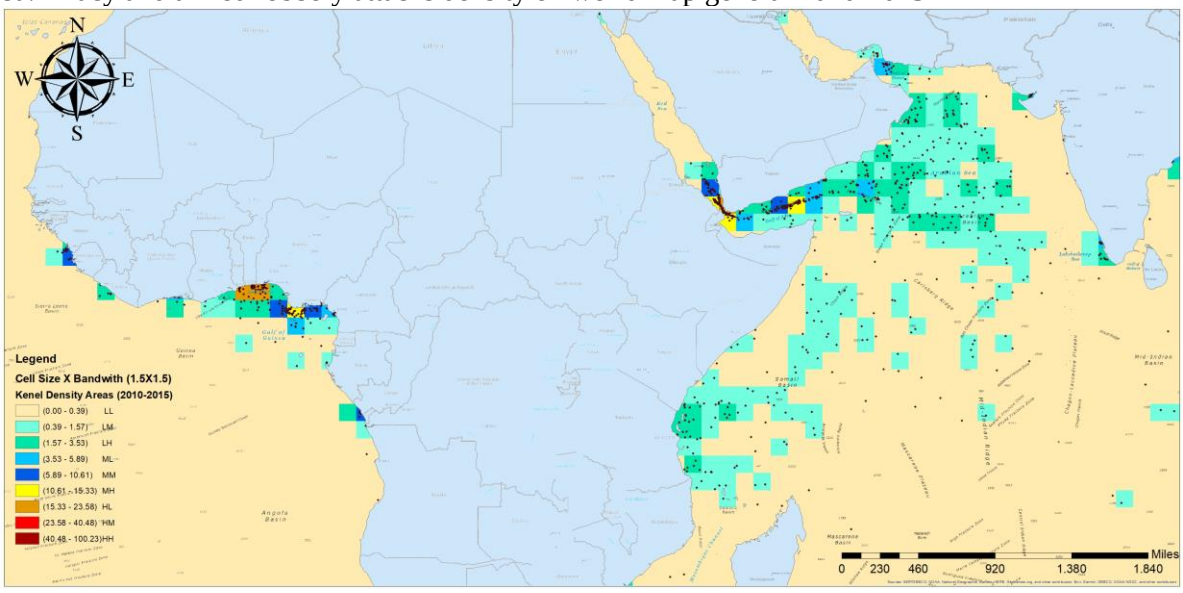


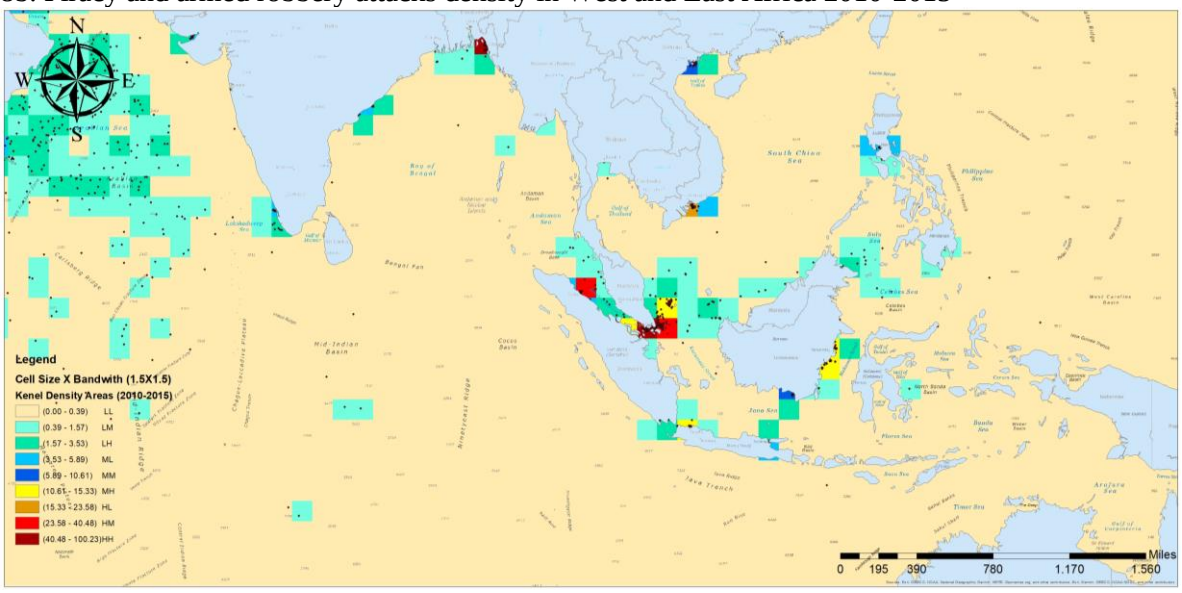
Figure 7. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2016 and 2021 (bandwidth: 15˚×15˚)



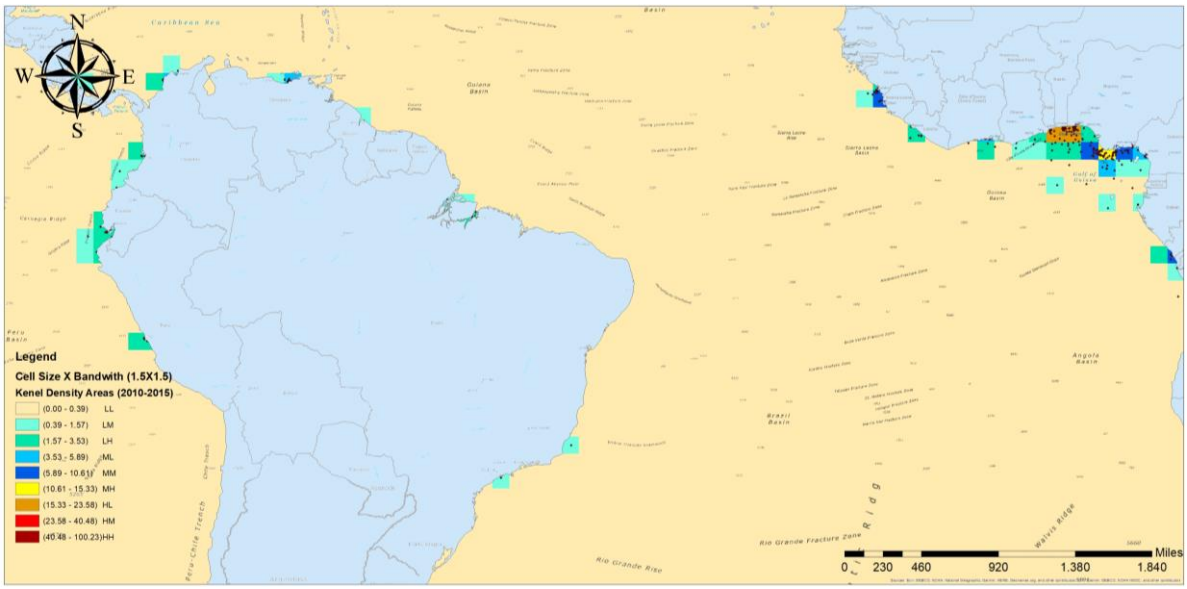
8a. Piracy and armed robbery attacks density on world map general 2010-2015



8b. Piracy and armed robbery attacks density in West and East Africa 2010-2015

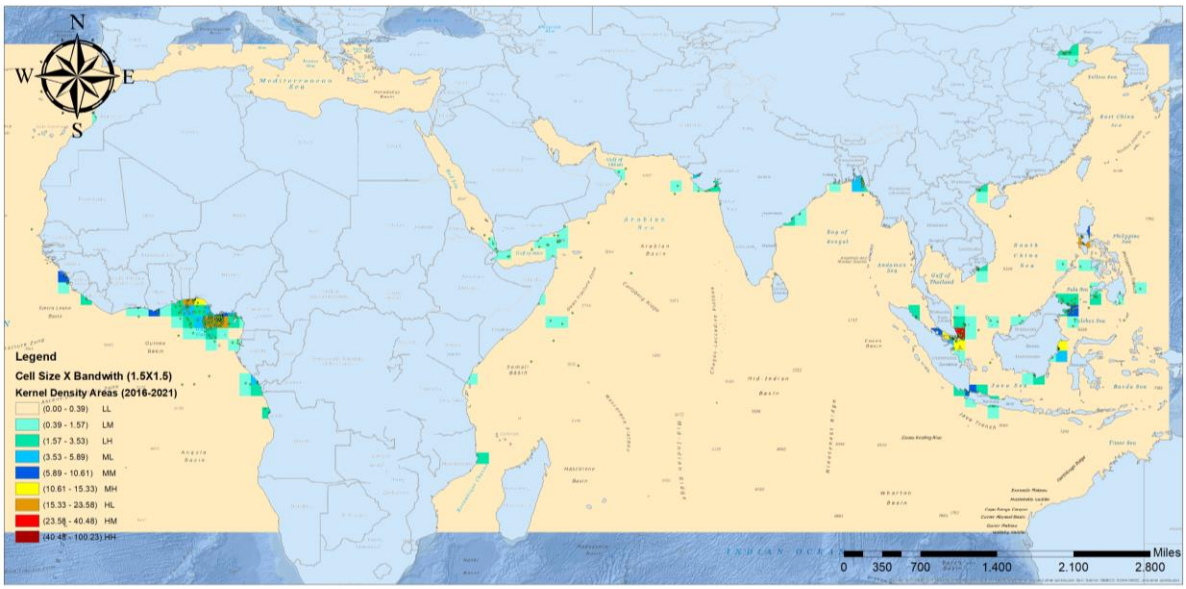


8c. Piracy and armed robbery attacks density in Asia 2010-2015

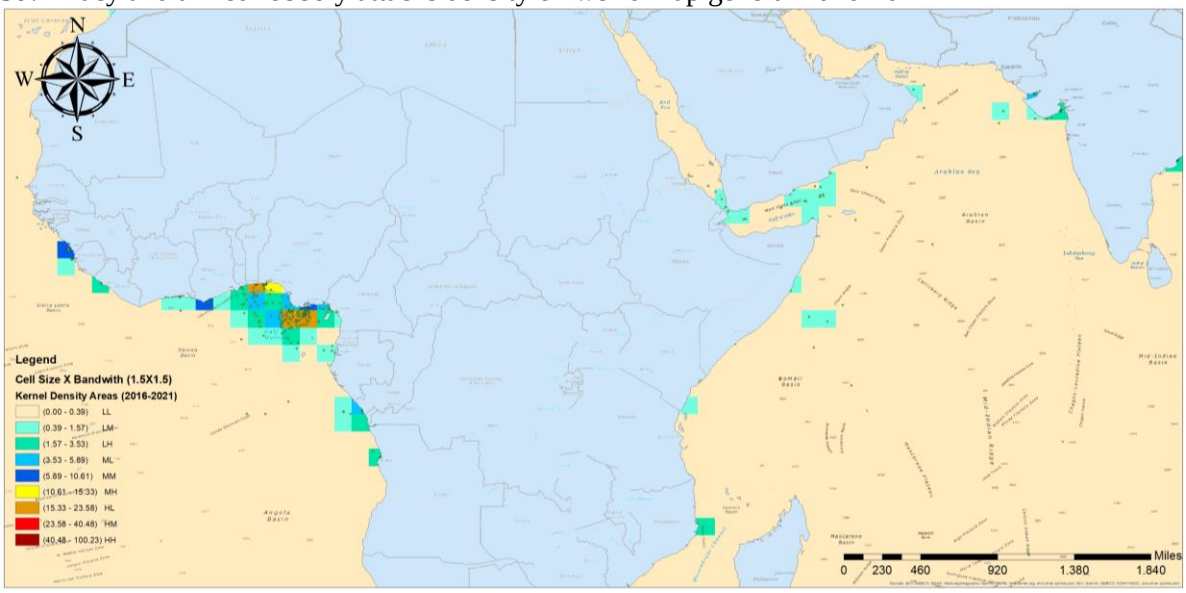


8d. Piracy and armed robbery attacks density in Central and South America 2010-2015

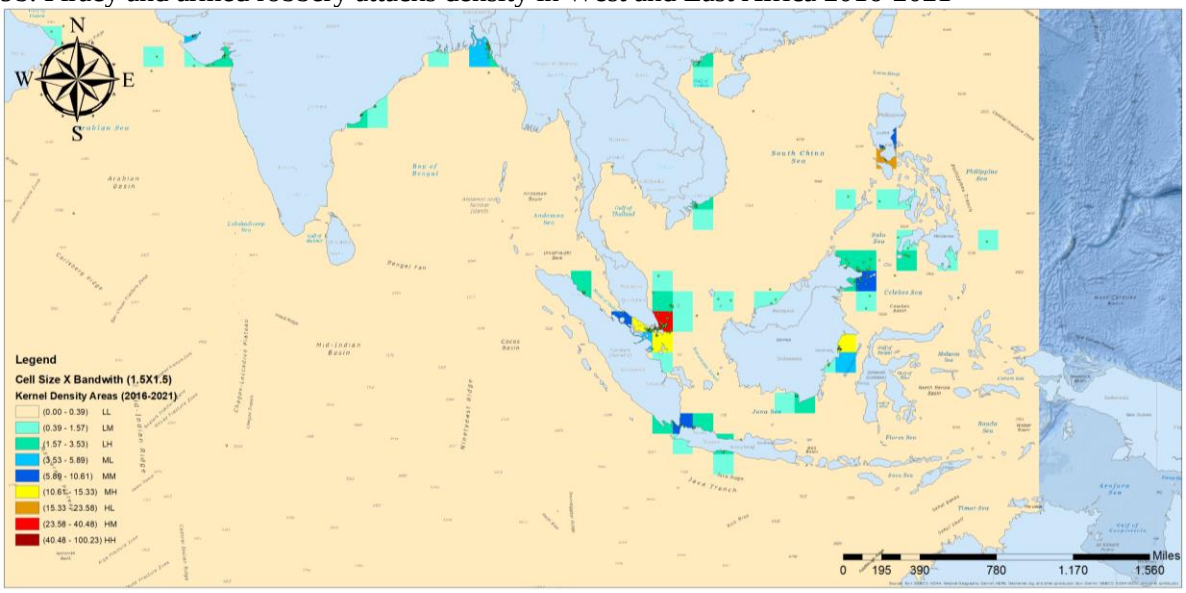
Figure 8. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2010 and 2015 (bandwidth: 1.5˚×1.5˚)



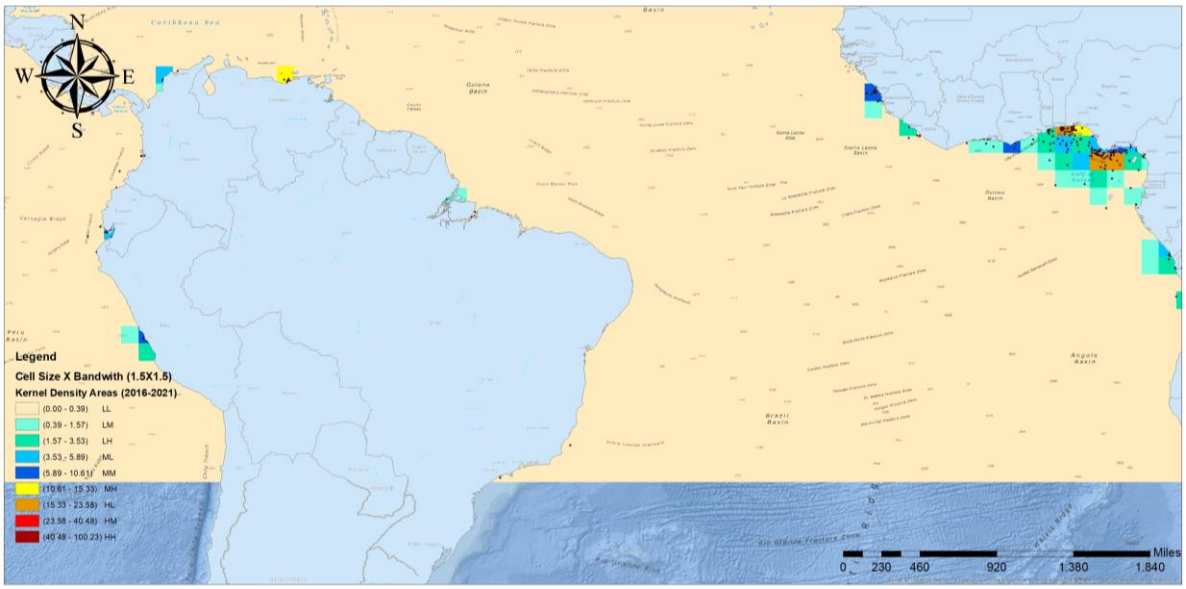
9a. Piracy and armed robbery attacks density on world map general 2016-2021



9b. Piracy and armed robbery attacks density in West and East Africa 2016-2021



9c. Piracy and armed robbery attacks density in Asia 2016-2021



9d. Piracy and armed robbery attacks density in Central and South America 2016-2021

Figure 9. Spatial density analysis of piracy and armed robbery attacks that occurred in all world waters between 2016 and 2021 (bandwidth: 1.5˚×1.5˚)