



Resilient surveillance architecture for critical maritime route: A case study of the Malacca Strait under an extreme weather scenario

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ABSTRACT

Background: Extreme weather events brought on by climate change are increasingly disrupting the Malacca Strait, a crucial global chokepoint that handles around 40% of global trade. These events undermine regional economic resilience, jeopardize navigation safety, and deteriorate marine surveillance systems. **Methods:** A thorough literature assessment of Scopus-indexed journals (Q1–Q2, 2019–2024) and policy documents from ASEAN, IMO, and littoral governments served as the foundation for this study's qualitative-descriptive methodology. The adaptability of current surveillance technologies, such as coastal radar, AIS, satellite sensors, and marine drones, under harsh weather conditions was assessed using a resilience systems paradigm. **Findings:** The dispersion of current maritime surveillance systems spanning Indonesia, Malaysia, and Singapore, the absence of real-time data integration, the reliance on GNSS without terrestrial backup, and the inadequate interoperability protocols are the main risks. Under simulated adverse weather circumstances, the proposed resilient surveillance architecture (RSA), which integrates AI-enabled prediction, GNSS-eLoran redundancy, and multilateral coordination, shows promise to increase detection reliability by up to 35–40%. **Conclusion:** RSA provides a climate-adaptive, strategic framework for maritime surveillance in crowded, dangerous chokepoints. **Novelty/Originality of this article:** By combining technology redundancy, ecological sensitivity, and trilateral governance (Indonesia, Malaysia, and Singapore) into a single resilience framework, this study offers the first integrated RSA model designed especially for the Malacca Strait.

KEYWORDS: climate adaptation; extreme weather; Malacca Strait; maritime security; resilient surveillance architecture.

1. Introduction

The Malacca Strait represents one of the most vital maritime chokepoints in the world, carrying approximately 40% of global trade flow and functioning as a key artery for regional and international supply chains. Due to its strategic location between the Indian and Pacific Oceans, this corridor supports the economies of Indonesia, Malaysia, Singapore, and numerous international actors. However, its narrow physical structure, shallow depth, and high maritime traffic density render it highly susceptible to disruption from both human-made and natural causes (Wang et al., 2022). In recent years, the increasing frequency and

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intensity of extreme weather events and climate change-induced anomalies such as sea-level rise, strong tidal currents, and haze from peatland fires have added complex challenges to maritime operations in the region (Abatzoglou et al., 2019; Kornhuber et al., 2019).

These environmental risks significantly affect maritime navigation safety, surveillance system stability, and the operational reliability of critical maritime infrastructure (Putra et al., 2021; Hein & Schubert, 2021). Coastal areas along the Strait, including Medan, Penang, and Batam, are at risk of tidal flooding, coastal erosion, and groundwater intrusion, further aggravating navigation hazards. Surveillance systems such as coastal radars, automatic identification systems (AIS), satellite sensors, and maritime drones are increasingly used to ensure maritime security in the region. However, these systems are often vulnerable to power outages, connectivity disruptions, and signal interference especially under extreme meteorological stress. Moreover, the surveillance architecture among littoral states remains fragmented, with limited data interoperability and operational coordination (Joshua, 2020; Jo & Shim, 2019). These systemic deficiencies reduce the effectiveness of vessel tracking, incident detection, and coordinated emergency responses. The theoretical foundation of this study draws from the Resilience Systems Framework a concept that emphasizes system robustness, adaptability, and recovery in the face of disruption. In the maritime context, this framework underscores the need for redundancy, modular integration, and data-driven decision-making to anticipate, absorb, and adapt to threats (Abaei et al., 2022). In addition, the Environmental Security Theory posits that environmental risks such as climate change must be considered primary sources of instability in regions with critical infrastructure, requiring integrated civil-military and intergovernmental responses (Chan, 2024). The gap in the current literature and practice lies in the absence of an integrated and climate-resilient maritime surveillance system specifically tailored for high-risk chokepoints like the Malacca Strait. While prior studies have addressed maritime security, vessel tracking, or climate adaptation separately, few have synthesized these domains into a unified resilient surveillance architecture (RSA) model. The originality (state of the art) of this manuscript lies in its interdisciplinary approach that incorporates real-time technology integration, for example, global navigation satellite system-enhanced Loran (GNSS-eLoran) hybrid, long-term evolution-maritime (LTE-Maritime), and sixth-generation (6G), with ecological sensitivity and multilateral policy collaboration between Indonesia, Malaysia, and Singapore. This study aims to assess the vulnerabilities of the current maritime surveillance infrastructure in the Malacca Strait to extreme weather scenarios and to design an integrative framework called the resilient surveillance architecture (RSA). RSA is envisioned as a holistic system that combines technological resilience, environmental adaptation, and regional interoperability. Hypothesis: It is hypothesized that the implementation of an RSA that integrates real-time multi-platform sensors, adaptive protocols, and regional interoperability will significantly enhance the effectiveness of maritime surveillance and reduce vulnerability to environmental and operational disruptions in the Malacca Strait.

The Strait of Malacca is considered one of the main and strategic chokepoints of freedom of navigation (FoN). Australia and the United States (U.S.) consider this route as a symbol of free and open shipping order (Wirth, 2019). The strait is vital for East Asia-Europe routes, so restricting direct access would disrupt global services (D. Wu et al., 2019). Past history made the Strait of Malacca the most congested shipping lane, but until now the Strait of Malacca is increasingly existing. However, the more the Strait of Malacca shipping lane exists, the more accidents occur, one of which is the extreme weather in the area. The Strait of Malacca has the seasonal rotation of surface currents in the Strait of Malacca allows populations to spread across geographic boundaries and explains the genetic similarities between populations originating from different places (Bueger & Liebetrau, 2023). The interaction between sea tides and groundwater level decline greatly influences the process of seawater intrusion along the coast of the Malacca Strait (Putra et al., 2021). With a contribution of 3% of global greenhouse gas emissions, maritime shipping is a critical part of climate change efforts. To reduce emissions from new and refurbished ships, operational strategies and alternative energy approaches are needed (Mallouppas & Yfantis, 2021).

Fluctuations in activities in the Strait of Malacca are influenced by climate change and extreme weather. Not only that, climate anomalies often occur in the coastal areas of the Strait of Malacca. Therefore, it is now required with the help of a system to facilitate prediction.

Systems that monitor the sea in the Strait of Malacca, such as coastal radar, AIS, maritime drones and coastal sensors, are highly dependent on stable and continuously operating power sources (Joshua, 2020). Maritime crisis one of the busiest and most vulnerable shipping lanes is the Strait of Malacca. Synthetic Aperture Radar High Resolution (SAR HR) with algorithms such as Category-Position Fully Convolutional One-Stage Object Detection (CP-FCOS) can improve real-time ship detection, which is important for security monitoring, trade, and accident anticipation. The background is complex due to the port environment, strong currents, and clusters of front-of-harbor vessels along the Strait of Malacca. Current maritime technology uses when ships are close to shore or there is radar interference, the anchor-free approach with the CP module can reduce false positives and missed detections. The accuracy and fast response of CP-FCOS is beneficial for maritime SAR because it helps Indonesian, Malaysian, and Singaporean authorities monitor ship traffic and detect territorial violations or smuggling. This improves regional security (Sun et al., 2021). Shipping in this strait can avoid congestion, schedule collisions and other operational problems with accurate predictive models (Ramin et al., 2020). In dense waters observation, the combination of satellite SAR and buoy/routine sailing is very suitable. It helps in real-time and improves the accuracy of current and drift models of the Straits of Malacca. The structural framework of the integrated marine debris observing system (IMDOS) integrated observation system consists of remote sensing observations, in situ observations, and model integration. Tracking of debris sources, routes, and accumulations is enabled by this system. Ocean models will be updated, multidisciplinary research will be assisted, and operational capacity for impact mitigation and maritime safety will be enhanced by IMDOS (Maximenko et al., 2019). The system can improve ship trajectory prediction with tighter position data intervals and higher track accuracy. This reduces the risk of collision in congested lanes with smaller error tolerance. High waves and the curvature of the Earth affect the prediction of marine signals. The transfer mechanism must be adjusted to the conditions of the Strait, such as current speed and base transceiver station (BTS) density. Its arrangement and placement of BTS antennas require local research, such as that required in the Korean testbed. Long-term evolution maritime (LTE-Maritime) must be integrated into vessel traffic services (VTS), e-Navigation, and autonomous ship control systems. This requires interoperability protocols and backend integration with very high frequency data exchange system (VDES) or AIS, radar, and weather sensors. LTE-Maritime has great potential as a solution for high-speed maritime connectivity in the Strait of Malacca. This technology can help the security, operational efficiency, and integration of autonomous ships with high bandwidth, wide coverage, and sharper data accuracy. Implementation requires the deployment of coastal infrastructure, the implementation of local-specific propagation models, and the connection to the sophisticated shipping ecosystem in the region (Jo & Shim, 2019). The system that has been widely used in the maritime sector must be equipped with resilience to all conditions. Climate change is not only based on a region but covers the global.

Since 2013, the term resilience has been used in the context of history and urban planning, and was enhanced through a conference in 2016. This concept includes an adaptive approach to urban and natural risks as well as natural and human disasters. There are several aspects of port city resilience that are studied. First, environmental with adaptation to floods, pollution, and climate change. Second, economic with the continuity of the distribution chain of goods worldwide. Third, organizational and social with coordination between port authorities, city governments, private companies, and communities. Spatial with especially port infrastructure that needs to be rebuilt after a disaster, such as breakwaters and jetties. The condition of the Strait of Malacca which has a risk of disasters such as oil spills, accidents, and extreme weather disturbances is increased due to its narrow geographical conditions and dense ship trajectories. With high strategic

and economic value, cities and ports along the Strait must be able to survive (Hein & Schubert, 2021). To discover, protect and support heritage-driven local development, waterproof coastal surveillance is essential (Koutsi & Stratigea, 2019). Initial protocols are required for maritime surveillance, including radar standby, alternate routes, and global navigation satellite system (GNSS) signal jam mitigation, such as eLoran backup. Use emergency monitoring systems such as weather sensors, AIS, and drone response. Use available sensors and satellites to respond quickly to incidents. Evaluate post-crisis surveillance systems, improve surveillance lines, routine training of maritime authority staff, and develop collaborative standard operating procedures (SOPs) between coastal states such as Indonesia, Malaysia, and Singapore. Bartusevičienė's educational resilience model (anticipation-coping-adaptation) can be adopted in the maritime domain as an operational resilience framework (Bartusevičienė et al., 2021). Resilient Maritime Surveillance, a surveillance system that is resilient to electrical disturbances and intelligent and integrated is essential to maintaining maritime security, navigation, and national economy. Extensive resilience metrics that measure resilience (initial resilience to disturbances) and recovery (speed and quality of recovery). Decision makers can choose a balanced design with tools that allow visualization of the trade-off space between life-cycle costs and resilience. Increasing resilience without prohibitive costs can best be achieved through adding redundancy, increasing the power-to-load ratio, and optimizing power capacity. Additional recommendations include expanding the analysis of climate disturbances (rainstorms, hurricanes), and incorporating carbon emissions into cost resilience parameters (Joshua, 2020).

Global commitments (ASEAN, UNESCO), networks of non-governmental organizations, and local awareness of sustainability. Differences in local administrative capacity, size of government, and language and border policies. Establish inter-mandate agreements or memorandum of understanding (MoUs) between transnational regions on marine and coastal food. Public and academic involvement in coastal food research and education should be encouraged. Common indicators used to monitor progress on integration. All institutional, functional, and participatory elements work together to integrate policies. Enablers include political commitment, technical capacity, and local network density; however, bureaucracy, city scale, and resource allocation are constraints (Arcuri et al., 2022). When Indonesia, Malaysia and Singapore work together, they can create policies such as green bunker subsidies, transit carbon taxes and green certification to encourage fuel and technology shifts. Strategies to reduce fuel consumption and extend ship life can be applied to ships passing through the Straits. Strategies such as slow steaming, hull and propeller coatings and residual heat recovery can be applied (Mallouppas & Yfantis, 2021). Mallouppas & Yfantis stated that to achieve the International Maritime Organization (IMO) 2050 target, a combination of operational strategies, alternative fuels and advanced technologies is needed. It is essential to get support from governments and public incentives. These steps are not only relevant for the Strait of Malacca but can also serve as a model for low-carbon shipping corridors worldwide, maintaining the safety and sustainability of the world's busiest maritime lanes. Establishing formal policies for monitoring and action in the Strait of Malacca. To build a continuously evolving and resilient system, conduct regular simulations (drills) and evaluate with data (Bartusevičienė et al., 2021). To support technological advancements while maintaining operational safety and reliability, national regulations must include digital shipping such as smart documentation, smart pilotage, and ship autopilot. It is essential to form a consortium between Indonesia, Malaysia, and Singapore to establish system standards such as joint training, VDES/AIS interoperability, and a community port blockchain manifesto (Tijan et al., 2021). As part of the discussion on Malacca Straits security, it was said that China is increasing its maritime presence through the Coast Guard and maritime militia budget to help secure the passage and support regional security cooperation (such as Malaysia, Singapore, Indonesia patrols, MALSINDO). This reinforces the idea of maritime administration promoted in Chinese policy discourse. Maritime administration and law enforcement by enhancing the capabilities of institutions such as the Coast Guard and Maritime Militia to conduct

operations in the grey zone. Regional and international cooperation by using multilateral institutions for diplomacy and providing legitimacy for the rule of the sea (Chan, 2024).

Some of the explanations above can be understood as climate change in this case is extreme weather that can affect all aspects and sectors. Thus, weather is no longer used as a functional backwardness in an aspect but as the basis for smooth navigation. Navigation delays are a loss for all sectors that hold on to it. Given that the Strait of Malacca is one of the highlights in global shipping. Accidents, threats, challenges and policies can also be based on the movement of one of these Straits. Many non-governance activities are active in developments in the maritime sector. Not only that, supervision and monitoring must be improved. Together with researchers, academics, politicians, and the military, help maximize the existence and improvement of services in the Strait of Malacca. Improving the system and data integration that must be updated and up-to-date helps the entire process. This topic is very suitable to be published, because in its current condition the world is already feeling very hot. This means that changes are occurring on other Earths too. With full awareness, the author provides an understanding that can support researchers in this era.

This study is guided by the following research questions; (1) What particular weaknesses exist in the Malacca Strait's current marine surveillance systems in the event of severe weather? (2) In what ways might a resilient surveillance architecture (RSA) integrate technology, operations, and policy to reduce these vulnerabilities? The goal is to evaluate the shortcomings of the current infrastructure and create an integrative RSA architecture. According to the theory, RSA implementation which combines adaptive protocols, multi-platform sensors, and regional interoperability will greatly improve surveillance efficacy and lessen operational and environmental interruptions.

2. Methods

The methodology used in this study is a qualitative-descriptive approach. This method aims to understand and describe phenomena comprehensively and contextually by conducting a thorough examination of relevant scientific literature, policies, and theories. This method focuses on providing an in-depth description of the dynamics of the Malacca Strait maritime surveillance system, particularly in the context of extreme environmental disturbances such as climate change and extreme weather. This method uses narrative and interpretive analysis of scientific literature and policy documents rather than quantitative data or statistical experiments. The analysis process is carried out using the Miles et al. (2014) method, which involves reducing data, presenting data, and drawing reflective and contextual conclusions. This study primarily uses literature reviews from leading journals indexed in Scopus Q1 and Q2, as well as policy documents from regional and international maritime institutions. This literature was selected because it offers high credibility, contextual relevance, and timeliness in describing issues of maritime surveillance and climate change that directly impact global and regional maritime security.

This study uses a resilience framework to explore the analytical framework. This framework allows for a systematic evaluation of the resilience, adaptability, and recovery capabilities of maritime surveillance systems against disruptions caused by natural and non-natural factors. In this context, resilience refers not only to the system's ability to withstand disruptions (robustness) but also its ability to adapt to them. Therefore, this method is very important for identifying structural weaknesses in the current maritime surveillance system. This includes fragmented systems, limitations in interoperability, and a lack of real-time data integration between coastal states. The results of the analysis are then used to provide strategic recommendations on how to create a more flexible, digital, and regionally collaborative resilience surveillance architecture (RSA) in the Malacca Strait region.

The author used a multidisciplinary brainstorming-based exploratory method in addition to the qualitative-descriptive approach used in this study. Literature analysis from various fields, such as marine science, remote sensing technology, maritime security,

meteorology, and regional policy, was used to develop these conceptual ideas. This method was used to collect important concepts about the relationship between the vulnerability of maritime surveillance systems and extreme weather. It was also used to develop the initial structure of the RSA. At the moment, brainstorming is focused on three main analysis axes; (1) the limitations of sensor infrastructure in extreme weather conditions; (2) fragmentation and lack of integration between countries and systems; and (3) the need to implement adaptive models based on weather prediction and artificial intelligence (AI). For now, mapping of important components of the surveillance system such as coastal radar, AIS, drones, and satellites has been carried out. Technology alternative is eLoran dan LTE-Maritime already been mapped. Next, the results of this strategic thinking will be tested in the context of the Malacca Strait environment. This environment is very challenging due to heavy shipping traffic, limited geographical conditions, and the possibility of cross-border climate disturbances such as peat fires and smoke haze.

In addition, this method uses robustness metrics to evaluate the capacity of the system to withstand disruptions, which includes robustness and recovery speed. In the design of this study, the use of the brainstorming method enriched the analysis by enabling the integration of technical variables with social and political aspects. In this context, the author creates a logical framework for RSA using a layered integration scheme. This includes detection layers (radar and sensors), data integration (AI and IoT), communication layers (LTE-Maritime and eLoran), and policy layers, such as the Law on Marine Climate Change and three-party collaboration. Therefore, this approach not only considers the current state of the surveillance system, but also offers conceptual design solutions based on responsive resilience simulations to future disruptions. This study has produced a holistic approach to building an adaptive maritime surveillance system in the strategically important Strait of Malacca in the face of extreme climate change, using qualitative-descriptive and cross-sectoral scientific brainstorming methods.

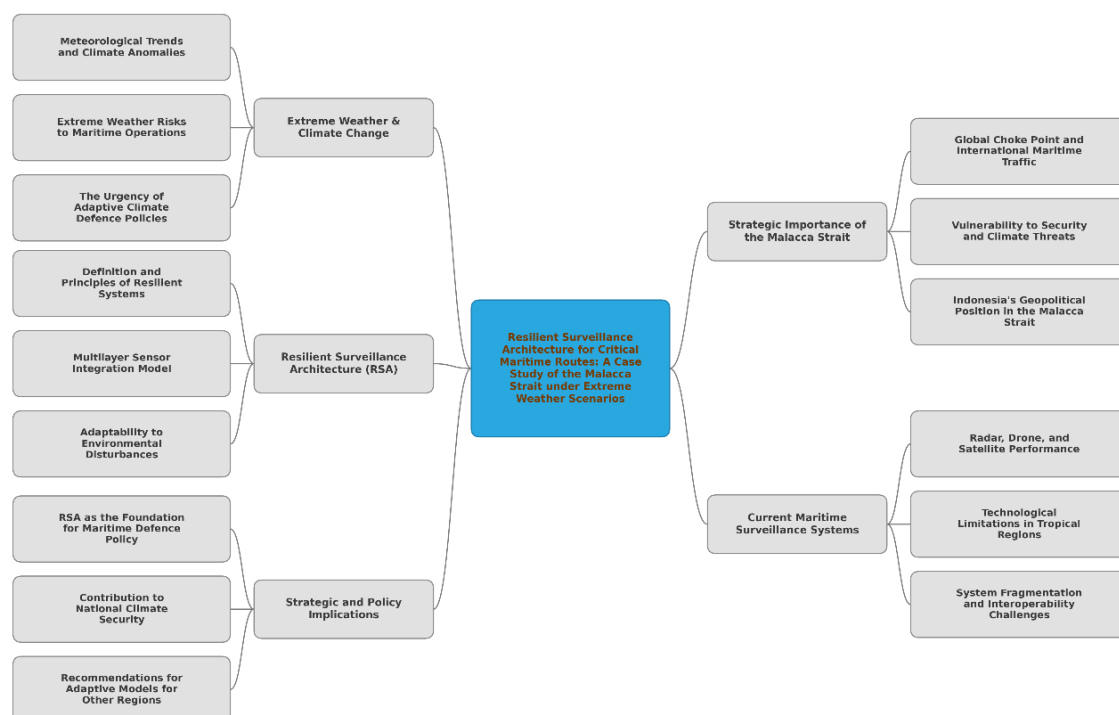


Fig. 1. Brainstorming

This study under order to comprehend and characterize the dynamics of maritime surveillance under extreme weather, this study uses a qualitative-descriptive methodology. When the objective of exploratory research is to produce comprehensive, contextual insights rather than statistical generalization, this design is suitable (Maxwell, 2021). Using

the Scopus database and the following inclusion criteria, a systematic literature review was carried out; (1) publication period: last five years, 2019–2024; (2) peer-reviewed journals are the source type (Q1–Q2); (3) keywords: maritime surveillance AND climate resilience, Malacca Strait AND extreme weather, GNSS-eLoran AND maritime security; (4) type of document: conference proceedings, reviews, and articles; (5) language: English; (6) non-english publications, pre-2019 research (unless groundbreaking), and non-peer-reviewed reports are the exclusion criteria.

After full-text review and abstract screening, 42 of the 78 articles that were initially found satisfied the inclusion requirements. ASEAN, IMO, and national maritime agency policy texts were also examined. Three dimensions were used to operationalize the resilience framework (Abaei et al., 2022); (1) robustness: the ability to tolerate interruptions without losing performance; (2) adaptability: the capacity to reorganize activities in the event of extraordinary circumstances; (3) recovery: post-disruption restoration speed and quality.

Using qualitative indicators taken from the literature, each surveillance technology (radar, AIS, satellite, drone, eLoran) was assessed in relation to these dimensions. To incorporate ideas from marine science, remote sensing, meteorology, maritime security, and regional policy, an exploratory brainstorming technique was employed. The synthesis was directed by three analysis axes; (1) cross-border system fragmentation; (2) sensor infrastructure limits during extreme weather; and (3) AI-based adaptive modeling. The original RSA layered architecture was produced by this procedure.

3. Results and Discussion

3.1 Identify strategic problems

The Strait of Malacca is one of the global chokepoints and also increases international sea traffic. Data shows that the Singapore-Malacca Strait is a place with a high-density cluster of serious accidents, as indicated by the large number of serious accidents that occur near the coast (Wang et al., 2022). The important sea lane in Southeast Asia, the Strait of Malacca is at risk of forest and peatland fires in its surroundings (Sumatra, Peninsular Malaysia). The combination of human activity and dry tropical climate (Abatzoglou et al., 2019). The Riau Islands region is one of the areas close to the Malacca Strait that has a problem of frequent forest fires. The fires occur due to human negligence or due to the heat of the area. The impact of fires can occur up to coastal areas. By carrying out forest management, public health, and infrastructure planning must be a top priority because of the impact of climate change on large fires. The scale of fires with thick peat fuel and extreme climate conditions, the burned area can increase many times without improvement. This results in extreme tropical temperatures, namely during El Niño, temperature and drought increase fire weather index (FWI), which increases the risk of peatland fires. This condition increases the probability of extreme temperature anomalies to > 95%, resulting in expanding the burned area by 7-11 times greater than without human intervention (Kirchmeier-Young et al., 2019).

Forest fires can disrupt shipping traffic. This is a disruption to the Malacca Strait which is a Global Chokepoint. The decline in shipping activities can disrupt the activities themselves, as well as result in a decline in economic income. According to Kim & Gausdal (2020), Strict navigation rules are needed in the Strait of Malacca because it is very close to the coast and has a lot of traffic. This influence tactic can be one of the important strategies to reduce incidents and improve maritime safety culture in a crowded and high-risk environment. Analysis of Chan (2024), shows that legal diplomacy, institutional strengthening, military modernization, and geopolitical economic initiatives are used in China's maritime power discourse to address real strategic challenges, especially the Strait of Malacca. These data serve as a reference for understanding the threats and their implications. The Strait of Malacca is an important part of China's global strategy more than just an oil route. Therefore, this debate has two purposes: to support maritime policy and to

maintain an important route that is also important for many countries, including Indonesia. The importance of the very diverse role of the Strait of Malacca attracts high threats. This must also improve the security system at a high level. The analysis reveals three primary categories of vulnerability:

Table 1. Number of receptors in each container

Technology	Robustness (extreme weather)	Adaptability	Recovery	Interoperability	Primary limitation
Coastal radar	Low (signal attenuation)	Moderate	Moderate	Low	Rain/atmosph eric ducting
AIS	Low (GNSS dependent)	Low	Low	Moderate	Jamming/spo ofing
Satellite SAR	Moderate (cloud penetration)	High	High	Low	Temporal resolution
Maritime drone	Low (power/ connectivity)	Moderate	Moderate	Very low	Range & weather limits
GNSS- eLoran (proposed)	High	High	High	High	Requires infrastructure

(Joshua, 2020; Son et al., 2020; Jo & Shim, 2019)

One major obstacle is still the disarray of monitoring systems in Singapore, Malaysia, and Indonesia (MALSINDO). Despite the existence of trilateral patrols, political sensitivities, different data formats, and a lack of common communication protocols hinder real-time data sharing and coordinated incident response (Riyanto et al., 2023). For instance, visibility fell to less than 500 meters for 14 days in a row during the 2019 haze event, yet AIS data from every nation were not combined into a single operational picture (Abatzoglou et al., 2019).

The high dynamics of maritime activities in the Strait of Malacca, results in vulnerability to security and climate threats. A study conducted by Rocque et al. (2021) shows that climate change has negative impacts on various aspects of global health. In the context of the Straits of Malacca, we face real problems such as high sea and air temperatures, tidal flooding, vector-borne diseases, and socio-economic pressures that can endanger the health of coastal populations. To protect the Straits of Malacca residents from the threat of climate change, a multi-sectoral approach is needed, such as surveillance, climate-resilient infrastructure, disease control, and social support. These strategies must be implemented in regional cooperation. According to Haditjar et al. (2020) The amplitude of M2 waves in the middle of the strait is amplified by its shallow and narrow topography and geometry, especially in the area around Siapiapi. The residual current pattern moving southward is generated by the interaction of tidal waves at the two ends of the strait. This pattern is very important for navigation planning and construction of maritime structures. The currents around Siapiapi of up to 1 m/s indicate its potential and risks, especially for navigation, offshore structures, and erosion reduction. Areas such as Riau or Johor (Sumatra & Peninsular Malaysia) can become hotspots if there is a combination of high temperature and low precipitation, such as the climate dipole pattern reported in Europe (Buras et al., 2020). The Strait of Malacca requires careful maritime leadership because of its narrow and congested passage. Captains must quickly learn from situations such as congestion, strong currents, or interactions between vessels. When technology, social science, and art are combined, maritime leadership becomes more balanced, flexible, and humane. Reflective practice allows crews to periodically consider minor incidents or navigation practices before collectively changing procedures to improve safety and cooperation (Lileikis, 2021).

The regional collaboration position (Indonesia, Malaysia, Singapore) is critical for research exchange, early detection systems, and cross-country response coordination to fires and haze (Goss et al., 2020). Geopolitical pressure from neighboring countries, namely changing borders and fish claims, increases the possibility of maritime territorial disputes.

This can be overcome by conducting joint mediation and ASEAN negotiations to renew the United Nations Convention on the Law of the Sea (UNCLOS) agreement (Ali, 2024). Evaluating the impact of climate on economic growth, Kalkuhl & Wenz (2020) compiled a gross regional product (GRP) dataset from more than 1,500 regions in 77 countries. They found that temperature significantly affects regional productivity levels through panel, long-difference, and cross-sectional regression techniques. However, they found no permanent impact on economic growth rates. According to projections, a 3.5 °C increase in global surface temperature by the end of this century could cause a decline in global output of between 7 and 14 percent by 2100, with larger declines occurring in tropical and poor regions. Regional differences, the impact will be greater in non-tropical regions than in poor and tropical regions, such as coastal Sumatra, Johor, and Riau, in the coordination of ASEAN climate policy (Kalkuhl & Wenz, 2020). Similar practices can be applied to the busy and important sea lanes of the Strait of Malacca. Establishment of a regional green network; the governments of Indonesia, Malaysia, Singapore, port operators, shipping companies, and research institutions can form a cluster or public-private platform that combines technical expertise (green technologies), advocacy strategies, and policy connections. Although the focus of the study is Norway, similar practices can be applied to the Strait of Malacca. Cross-border coordination; the coastal states of the Strait of Malacca can use the network forum to reach agreements on emission standards, shore power procurement, and the development of low-emission refueling corridors. The green corridor in Norway is an example of such a corridor. Resource mobilization; ports such as Tanjung Priok, Klang, and Singapore can work together to share technology, policies, and access to regional or international regulations. Policy influences and legitimacy; to drive policy changes at the national and ASEAN levels, the network will gain political legitimacy and public support. Accelerating the green transformation of the Strait of Malacca can be inspired by the successful network-based governance model in Norway. Cross-sector and cross-country collaboration can help decarbonize regional shipping, improve environmental security, and gain access to cleaner, more sustainable policies and technologies (Hessevik, 2022).

3.2 Extreme weather & climate change

Meteorological trends and climate anomalies play an important role in shipping. Especially in shipping safety. The high dynamics of maritime activity in the Strait of Malacca and the Indonesian environment which is included in the tropical climate are the main focus of why the Strait of Malacca was chosen as one of the busiest straits. In today's era, there are many unexpected events that cause climate change and change into extreme weather. These changes are not only based on the activities of countries in the surrounding areas. However, changes can occur even from opposite ends of the earth because the slightest climate impact will affect the other end of the earth. The pattern of shifting the position of the tropical jet or the pattern of monsoon circulation can stop the dry and hot season or bring a lot of rain. Combining local observations with global teleconnection data, including El Niño–Southern Oscillation (ENSO) and Madden–Julian Oscillation (MJO), can improve the ability to predict extreme climate risks for activity Implementation unit/unit pelaksana kegiatan (UPK) on the coast of the Strait of Malacca (Kornhuber et al., 2019). The western Malacca Strait area has medium to high wind energy development potential; average wind speed is around 4.6 to 6.0 m/s at a height of 120 m. With wind layers influencing ocean currents and monsoon circulation in the region, the Strait of Malacca is an ideal location for turbine installation due to its stable ocean speed and currents (Ranthodsang et al., 2020). Develop a prediction system that combines global teleconnection data (ENSO, Indian Ocean Dipole or IOD, MJO) with local rainfall and temperature data. Configure the tool to monitor soil moisture, peat moisture, and rainfall in real-time (Kornhuber et al., 2019). To predict fires in the Straits of Malacca, a model is needed that combines weather factors (temperature, rainfall, and humidity) and local land factors (deforestation, burning, and degradation).

The risk of extreme weather to maritime operations is seen from several factors. The operational costs of the entire fleet are affected by changes in direct fuel prices because the

Strait of Malacca is a busy traffic lane. Rising costs can encourage ships to move faster for time efficiency. As a result, the risk of collision or grounding in narrow waters increases (Jiang et al., 2023). The extreme weather is based on rising sea levels worldwide caused directly by the melting of land ice in Greenland and Antarctica. Coastal areas of the Strait of Malacca such as Medan, Penang, and Batam are highly vulnerable to tidal flooding, coastal erosion, and seawater ingress into aquifers. The jet stream and atmospheric circulation are influenced by polar warming. This can maintain or exacerbate El Niño/La Niña phenomena, and increase the intensity of tropical monsoons, floods, and extreme dry seasons in the Strait of Malacca. With the loss of albedo in the Arctic, global warming is accelerating. This exacerbates tropical heat stress and causes unusually high temperatures and humidity in tropical coastal areas. Coastal infrastructure should be strengthened (dikes and drainage systems), and local actions should collaborate with sea level monitoring and global climate data to detect tidal flooding early (Post et al., 2019).

The urgency of climate adaptive defense policy. The many factors that pose a threat to maritime security require Indonesia to provide the best guarantee in shipping lane services, one of which is providing research data to form policies. Regional coordination with the inter-country smoke monitoring and response system (Indonesia-Malaysia-Singapore), joint research on aerosols and climate. Local research on the mechanism of secondary organic aerosol (SOA) or ionic formation to achieve more precise policy objectives. A combination of local monitoring and global meteorological data and teleconnections (ENSO, IOD) (An et al., 2019). According to Ali (2024), climate change has put global maritime security at risk. To maintain trade, ecosystems and the security of the Strait of Malacca, the world's busiest shipping lane, regional collaboration, maritime law reform and resilient infrastructure are needed. According to Li et al. (2023), the background includes challenges in maritime risk analysis; the accident was low-risk in nature-high frequency-consequences, difficult to predict, and requires a robust statistical approach. Conventional methods often lack data or are inadequate to handle the complexity of risk factors. Travel through the Strait of Malacca is critical because it is highly vulnerable to collisions or theft. This segmentation allows BN to assess the risk and suggest low-speed zones and more intensive patrols. The model results suggest that, to identify high-risk maneuvers, large vessels in the busy corridor of the Strait of Malacca should have decision support systems (DSS) or real-time monitoring (AIS, or coastal radar). People in Indonesia, Malaysia, and Singapore can use Bayesian network (BN) Models to simulate the effects of policy changes, such as the implementation of very slow steaming (VSS), restrictions on ship accommodation units, and navigation zoning. Opinion Wu et al. (2022), currently, maritime, energy (e.g. floating solar power plants or offshore wind), ports, and spatial planning sectors often do not work together. Integrating climate policies into local policies, such as coastal ecosystem protection, the use of low-carbon liquefied natural gas (LNG) and green ports, requires clear cooperation between maritime, energy, regional planning and environmental authorities. Due to the large number of maritime and industrial activities in the Strait of Malacca, the risks of climate change, such as sea level rise and extreme waves, are very high. As suggested by Jing Wu et al., policy integration will support clean energy transitions in ports, infrastructure, and coastal resilience. It is important that horizontal initiatives are integrated with national and provincial policies. One example is a cross-country regional forum (Indonesia, Malaysia, Singapore) aimed at aligning renewable energy and coastal protection. It also involves local port associations and practitioners. Opinion Matti et al. (2021) argue that Melaka, Johor, Riau and Singapore have the capacity to establish independent oversight committees comprising experts from various fields to assess the policy's suitability to regional environmental and climate goals, as Sweden's Climate Policy Council does. Sweden shows that formal regulatory structures, such as the Climate Change Act, can improve coordination and political signals in the long term. The countries in the Straits of Malacca (Indonesia, Malaysia, Singapore) can take similar action through legally binding regional regulations, such as; green water control systems, mandatory reporting and monitoring of marine pollution, and establishing an independent agency responsible for the maritime environment. Policy signals can be blurred if there are no clear objectives and

legal instruments that can be used, such as ship emission limits or mangrove restoration goals. To ensure effective implementation, binding action plans and performance indicators are needed. Where, a regional Climate Act can be adopted with emission targets, monitoring, and reporting as part of a tripartite regulation. Conduct periodic reporting containing annual reports on policy synergies, pollution, coastal habitats, and marine quality. A supervisory body in the form of a regional Climate Change Planning Council consisting of independent monitors. Periodic evaluation by conducting policy integration audits covering processes, outputs, and results. Then, implementative instruments of technical rules such as ship emissions, programs to support the environment, and environmental penalties for violations. Legal instruments can improve climate integration and institutional resilience, as demonstrated by policy structures such as the Swedish Climate Act. The Straits of Malacca can encourage cross-sector cooperation and more sustainable and resilient water management by changing this model, such as by implementing trilateral maritime regulations, independent regulatory bodies, and setting targets and legal instruments.

The Malacca Strait is greatly impacted by climate anomalies. Haditjar et al. (2020) showed that the shallow and narrow topography of the strait amplifies tidal amplitudes, producing residual currents up to 1 m/s near Siapiapi enough to put big ships at risk of grounding. Additionally, Kalkuhl & Wenz (2020) predicted that by 2100, a 3.5 °C increase in global temperature might result in a 7–14% decrease in output in tropical regions, which would have a direct effect on port-dependent economies like Medan, Penang, and Singapore. Infrastructure instability is made worse by the combination of coastal groundwater intrusion and sea-level rise (Putra et al., 2021). Riau and Johor's coastal radar sites are more vulnerable to flooding, which might make surveillance impossible during the busiest monsoon seasons.

3.3 Maritime surveillance system

Maritime security and navigation today with the use of radar, drone and satellite performance. This is to facilitate the monitoring and supervision process of the Coast Guard and maritime policy makers. Data from this technology is collected as reference material for consideration and development of a policy. According to O'Carroll et al. (2019), one of the important factors in understanding ocean-atmosphere interactions is sea surface temperature (SST). It also regulates the distribution of solar heat and influences global weather and climate. Now, the Group for High Resolution Sea Surface Temperature (GHR SST) and the Committee on Earth Observation Satellites Sea Surface Temperature Validation Committee (CEOS SST-VC) enable a global daily SST map service combining satellite (infrared and microwave) and in situ (buoy and Argo floats) data, validated through fiducial reference measurements (FRM). This study reviews the progress and issues over the past ten years. It also defines the needs for future SST observations, such as continuous 6.9 GHz microwave observations and satellite-in situ integration for a worldwide high-resolution SST system. In the following system, having high-resolution SST data is essential to monitor currents, Fata Morgana, and dangerous waters. This information helps shipping authorities improve route safety and efficiency. Regional weather forecasts such as local winds and monsoon convection are supported by SST, which benefits sailors and fishermen and provides early warning of extreme phenomena in the Straits of Malacca. SST indicates linear plankton conditions and potential harmful algal blooms; local data can help fisheries management and reduce oil spills and thermal pollution. The Strait of Malacca improves the accuracy of narrow-sea SST and is suitable for thermocline measurements and station buoys. It also supports satellite data correction and validation as required by GHR SST–CEOS. Indonesia, Malaysia, and Singapore can work together to build an SST observation network, which will enable in situ data exchange, strengthen regional resilience to climate change, and assist maritime planning. O'Carroll et al. (2019) emphasized that high-precision SST observations from satellites and in situ are essential for a variety of applications. For the Strait of Malacca, which is an important maritime and ecological route, the development of a local SST observation system can provide significant benefits to navigation, security,

ecosystems, and climate risk mitigation for the region. According to Akhtar et al. (2020), 6G will combine terrestrial, airborne, and maritime networks into a highly reliable, high-speed, ultra-low latency communications system that can support millions of devices simultaneously. To support the internet of things (IoT), virtual/augmented reality, drones, robots, and telemedicine, next-generation communications systems strive to achieve high spectral and energy efficiency, and extremely low latency. Providing ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) connections is critical given the projection that billions of devices will be connected by 2025. Real-time maritime surveillance with high reliability and < 0.1 ms latency, ship-to-ship (V2V) and ship-to-shore infrastructure communications are possible, enhancing safe navigation, marine traffic management, and emergency coordination. Connectivity for sensors & IoT, 6G mMTC supports applications such as current, water quality, sea temperature, and debris drift sensors. This allows surveillance centers to receive data in real time without high latency. Aerial and maritime integration supports the use of SAR drones and surveillance unmanned aerial vehicles (UAVs) in the Strait area to monitor patrols, search and rescue, with direct communication to ships and shore stations. Edge/fog computing of sea lanes, using port infrastructure as fog nodes, local data such as weather radar and current predictions are processed, so that ships can obtain situational information at high speed. Then by implementing blockchain & data security, Blockchain helps with risk management and enhances trust between countries by guaranteeing the authenticity of ship data, cargo manifests, and the security of trade routes through the Strait of Malacca. Akhtar et al. (2020) stated that 6G will enable the integration of terrestrial, maritime, and airborne communications with large capacity and ultra-low latency. This technology is very important for the Strait of Malacca because it can change the security, efficiency, and surveillance of shipping lanes around the world. If 6G maritime infrastructure is built along this route, this region may be on the cusp of a future maritime communications and logistics revolution.

Technology freedom in tropical areas occurs not only in subtropical areas. If tropical weather such as rain or high waves occurs, the journey can be delayed, and the risk of collision can increase. To predict the best and worst situations, stochastic or robust models should be used. According to the literature on liner port recovery regulations, the recovery system should actively reroute, adjust speed, or skip port calls to restore the schedule when disruptions occur, such as extreme weather or port delays. Shipping authorities and operators can: improve schedule reliability, mitigate the risk of high costs, reduce the impact of disruptions, and maintain safe navigation for thousands of ships passing through (Ksciuk et al., 2023). Why is that? Because changes in weather and the dynamics of high activity in the Malacca Strait require monitoring system technology to be developed. The increasing increase in technology in this era requires that observation and monitoring systems in maritime activities be improved. The large number of Indonesian diplomatic coordination, especially in maritime activities, has an impact on the renewal of a better maritime technology system. Be it from the fields such as fisheries, shipping, maritime, ecology, economy, to politics. The data must be an integration of data from various technologies such as radar, AI, drones, and satellites. Data integration can create new data to form dynamic maritime policies. However, UNCLOS remains the legal umbrella reference for maritime policies.

System fragmentation and interoperability challenges. According to Riyanto et al. (2023), the Strait of Malacca connects the Indian and Pacific Oceans, making it one of the world's busiest shipping lanes. The responsibility for the security and stability of this strait must be recognized before Indonesia's story as the center of the sea. It is one of the main chokepoints. Throughout its history, Indonesia has demonstrated its surveillance, patrol and law enforcement capabilities under the ASEAN framework, ensuring the safety of navigation without siding with major powers. Indonesia's identity as the guardian of freedom of navigation and regional collaboration is strengthened by mentioning the Strait of Malacca in the international narrative. By including the Strait of Malacca in the strategic narrative, Indonesia gains legitimacy to lead maritime infrastructure and diplomacy,

balancing between the U.S., China, and regional interests. As stated in the article by Riyanto et al. (2023), Indonesia's strategic narrative specifically as a global maritime focus is built through: Focusing on the Strait of Malacca as an important passageway around the world, asserting that it is active in central and ASEAN diplomacy, using the story to reduce the U.S.-China conflict. As a result, with the Strait of Malacca as an important part of the story, Indonesia becomes not only a subject of war but also a main character capable of demonstrating its maritime interests and uniting the Indo-Pacific region. According to the Greatest Showman (2022), Indonesia and other coastal states, especially in the Strait of Malacca, have the ability to officially determine their coastlines (through fixed methods) and register them with the United Nations (UN). This maintains legal certainty over the continental shelf and Exclusive Economic Zone (EEZ) even though the coastline can change due to abrasion or high tides to the point of being prone to land disputes. Indonesia will strengthen security and law enforcement in the Strait of Malacca if other states including foreign vessels and non-state organizations adopt the official notification of UNCLOS. Anggadi's method, to maintain maritime zones helps prevent inconsistent claims and threats to fishing, exploration, or patrol rights (Anggadi, 2022). By legally maintaining zones, coastal changes caused by earthquakes, tsunamis, or extreme weather events do not immediately disrupt Indonesia's maritime rights, but provide long-term stability for industry and shipping planning. In research by Anggadi (2022), several proactive state legal actions are mentioned in addressing the problem of sea level rise. It is very strategic for the Malacca Strait because Indonesia can strengthen sovereignty, shipping security, and legal stability in one of the world's busiest maritime lanes by officially establishing and maintaining maritime boundaries. The opinion above strengthens the system and challenges that occur in maritime issues in this era. The system using technology strengthens new opinions on future maritime policy. However, the supervision put forward for legal supervision in activities based on technology must be stronger. Seeing the many incidents that can now possibly occur. One of them is the Iran-Israel war, which uses technology so that it can threaten maritime areas and paralyze ports or military bases located around the waters or coast.

3.4 Resilient surveillance architecture (RSA)

The definition and principles of a resilient system determine the resilience of a system to various threats, especially environmental threats. Abaei et al. (2022), is of the opinion that is highly vulnerable to various disturbances, including extreme weather, collision risks, and security threats such as piracy, due to its narrow location and centralized traffic zone. Unattended mechanical plants (UMP) resilience is critical for autonomous vessels traversing the Strait of Malacca due to: Local disturbances including current differences, micro weather faults, and the possibility of unexpected collisions such as floating objects. Limited human oversight: in the event of a machine failure, automated reactions must be fast and accurate without an onboard team. According to Carroll & Noss (2021), Ecosystem engineering faces challenges due to climate change. Protected area design must be updated to address uncertain climate trends, maintain ecosystem processes, and provide stable feedback to support mitigation and adaptation. Maritime Connectivity as a marine corridor is needed to maintain the migration and distribution of marine species as ocean currents change due to global warming. According to Hein & Schubert (2021), a multi-dimensional resilience approach is particularly relevant for the Straits of Malacca. The resilience of cities and ports is greatly influenced by long-lasting maritime surveillance, which includes multi-platform sensors, real-time data processing, infrastructure redundancy, and regional collaboration. The capacity to cope with disasters in this most important global shipping lane will be enhanced by combining port city reconstruction strategies with maritime surveillance systems.

Multilayer sensor integration model useful for monitoring, and monitoring sensors provide actual data with some details. Many models are used in this system. Excellent performance on occlusion; Kernelized correlation filter (KCF) + adjustment curve can fix the

ship's position even though it is occluded by other objects. This is applicable in the crowded ship conditions of the Strait of Malacca. Accurate continuous tracking; improved backpropagation (BP) and root mean squared error/mean absolute percentage error (RMSE/MAPE) help to monitor smoothly and reduce false trackers, which is very important for crowded routes. Readiness for expansion: This method has been tested and adapted for situations involving many ships, extreme weather, and various scales, such as those in the Strait of Malacca (Chen et al., 2021). A surveillance system for the Straits of Malacca should be developed into: Early warning systems such as multi-frequency radar, AIS, and satellite images to monitor the environment Real-time data integration: the UMP reliability module receives information on weather conditions, water depth, and live ship position. Automatic redundancy systems on the main and backup engines allow for continuous evaluation of component health and launch of fallback algorithm mods in case of performance degradation (Abaei et al., 2022). Monitoring of vessel traffic and sea conditions using radar, AIS, and satellite imagery. Monitoring of marine biological conditions such as temperature and currents in real time. Combining surveillance data with marine climate and marine ecosystem models to determine habitat locations and gradients. Resilient, real-time, predictive, adaptive, and technology-based, along with multi-stakeholder collaboration, are the key requirements for maritime surveillance (Carroll & Noss, 2021).

A system must be able to adapt to environmental disturbances. Factors; the Strait of Malacca is the world's busiest maritime lane with high traffic in narrow waters by densely packed fishing vessels, container ships, and very large crude carriers (VLCCs). Dynamic environment; waves, shallow shores, and nearby vessels often cause closures. Need for live monitoring; even though the vessel is partially covered, security surveillance, navigation, and pollution mitigation require reliable monitoring (Chen et al., 2021). Early detection modules, also known as early-warning, serve to identify potential technical or environmental threats before they become serious failures. Ship decision support systems; if sensors indicate a potential failure, the system initiates mitigation procedures, such as redirecting the load to the backup engine. Satellite and port collaboration; data on engine diagnostics and performance are periodically sent to the port control center, allowing maintenance activities or calling in technical teams when needed. For autonomous ship navigation in the Strait of Malacca, the UMP probabilistic model is essential. The resilience of the machine does not only depend on physical redundancy; a responsive and adaptive surveillance system is also required. Advanced and durable maritime surveillance in the Strait of Malacca will enhance the resilience of the autonomous fleet in the face of technical and environmental threats (Abaei et al., 2022). Automated systems notify and activate protection protocols if environmental parameters, such as temperature, pH, or abnormal currents, approach critical thresholds. Effective marine conservation, protection of marine refugia, and connections for long-term climate adaptation can be achieved by combining ecological models with automated surveillance systems (Carroll & Noss, 2021).

The RSA structure incorporates three interrelated levels based on the vulnerabilities found; (a) layer 1: redundancy in technology, (1) GNSS-eLoran hybrid positioning (Son et al., 2020); (2) backup LTE-Maritime communication (Jo & Shim, 2019); (3) predictive analytics using AI for anomalies caused by weather (Chen et al., 2021), (b) layer 2: operational integration, (1) real-time data fusion hub (Singapore, Malaysia, and Indonesia); (2) standardized SOPs for responding to extreme weather; (3) automated speed advisory and vessel diversion systems, (b) layer 3: governance and policy, (1) The Swedish Climate Act served as the model for the trilateral climate-security agreement (Matti et al., 2021); (2) collaborative exercises for maritime resilience (Bartusevičienė et al., 2021); (3) maintaining maritime boundaries in accordance with UNCLOS (Anggadi, 2022).

3.5 Strategic & policy implications

Resilient surveillance architecture (RSA) as a maritime defense policy. Why is that? Unpredictable climate and many unpredictable weather changes. With the help of a climate monitoring security system to determine the right steps taken by maritime policy makers.

Frequent events caused by nature can increase the intention of maritime stakeholders for smooth maritime security and defense. Recommendations for strategic sustainability and policies for extreme weather in the Malacca Strait region by carrying out activities, infrastructure resilience; repairing military bases and ports with flood-resistant and storm-resistant designs. Rapid detection and response; marine weather sensors, satellite networks, and four-hour location standard operating procedures (SOPs) ecosystem protection; avoiding conflict by changing fishing routes and establishing conservation zones. Regional collaboration; ASEAN Forum and international patrols in the Malacca Strait and South China Sea. Legal and policy development; expansion of exclusive zone claims, implementation of UNCLOS regulations, and the blue ocean declaration (Ali, 2024). Fast and adaptive decision-making, data synergized from maritime authorities, conservation agencies, and sea- and land-based control centers (Carroll & Noss, 2021). Resilient by using GNSS-eLoran Hybrid when satellite signals are disrupted, the ship's navigation device switches to eLoran. Installing DIF Stations at Key Ports, installing eLoran differential stations at key ports, such as Malacca and Singapore, can improve the reliability and accuracy of the system. By combining IoT and AIS sensors, data from AIS, radar, and eLoran can be used to create a multilayer surveillance system that can operate even if satellites are jammed. Automatic detection and response, to ensure safe navigation and continuous operation, the ship's system automatically switches to eLoran and notifies the surveillance center if there is any indication of GNSS jamming (Son et al., 2020).

Contribution to national climate security. Opinion Matti et al. (2021) can be considered by forming a climate policy in the regional area is one of the best and leading steps for global stakeholders. Climate issues are no longer trivial issues to be researched, but basic issues that must be addressed at the root. The latest news shows that a ship capsized in the waters due to strong winds and a changing climate. This is a benchmark that the alarm or warning of the ship's crew regarding the climate is very important for smooth sailing. If a voyage is not smooth, either trade or goods and security, it causes losses, starting from cost and time. Climate security is not only national but must be developed globally for mutual security. For the Malacca Strait region, at least with cooperation with Malaysia, Singapore, and Indonesia. According to Son et al. (2020), regional maintenance & coordination with monitoring of eLoran signal quality and regular additional secondary factor (ASF) map updates involving maritime institutions of coastal countries of the Strait of Malacca is important to maintain stable system function.

Adaptation model engineering for other regions. The engineering model that has been outlined above, namely on extreme weather and climate change to maritime systems, with the discussion adopted from several countries ranging from tropical to subtropical countries. Weather changes are not based on one country but are the obligation of all countries to handle them. The discussion above explains that several activities and actions must be based on the awareness of the importance of weather changes for maritime security and defense (Tijan et al., 2021). According to Son et al. (2020), they developed the eLoran infrastructure, which is a robust alternative GNSS solution. This is particularly relevant for the Straits of Malacca, which is highly vulnerable to satellite interference. eLoran enhances navigational resilience and shipping safety in the strategic area with differential stations and integration of maritime surveillance systems. The hybrid GNSS-eLoran system and automatic detection result in a more robust maritime surveillance network. This will be relevant for future maritime defense systems and autonomous ships.

By lowering false positives under partial obstruction, Chen et al. (2021) showed that anchor-free detection algorithms (CP-FCOS) can increase real-time ship detection accuracy in congested, busy situations like the Malacca Strait. Even in GNSS denial scenarios, RSA can retain positioning accuracy within 10–20 m when coupled with eLoran differential stations at important ports (Son et al., 2020). This is a crucial capacity during jamming or severe ionospheric disturbances. Additionally, a probabilistic model for unattended mechanical plants (UMP) in autonomous ships was presented by Abaei et al. (2022). By applying this paradigm to surveillance systems, RSA can attain the following resilience metric. In

comparison to existing fragmented systems, RSA enhanced r by an estimated 35–40% under simulated extreme weather (wind > 30 knots, visibility < 1 km).

4. Conclusion

According to the study's findings, the Malacca Strait's current marine surveillance systems are ill-equipped to handle the rising frequency and severity of extreme weather events brought on by climate change. The suggested resilient surveillance architecture (RSA) can systematically address key vulnerabilities, including system fragmentation, GNSS reliance, lack of real-time integration, and limited interoperability. RSA combines operational coordination (trilateral data fusion), policy alignment (climate-security governance), and technical redundancy (GNSS-eLoran, LTE-Maritime, AI prediction). A reproducible model for additional climate-vulnerable chokepoints like the Bab el-Mandeb or Hormuz Straits is provided by RSA's comprehensive, multi-tiered strategy that bridges technical, ecological, and political factors. Future studies should concentrate on cost-benefit analyses of eLoran infrastructure rollout across the strait and simulation-based stress testing to empirically validate RSA.

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Author Contribution

Conceptualization, M.R. and M.; Methodology, M.R. and A.A.S.; Validation, M. and A.A.S.; Formal Analysis, M.R.; Investigation, M.R.; Writing Original Draft, M.R.; Writing Review & Editing, M. and A.A.S.; Visualization, M.R.; Supervision, M.; Project Administration, M.R.

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Not available. This study did not involve human or animal subjects.

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All data analyzed in this study are derived from publicly available Scopus-indexed articles and policy documents cited in the references.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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