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Resilient Surveillance Architecture for Critical Maritime Routes: A Case Study of the Strait of Malacca under Extreme Weather Scenarios

Yosyea Oktaviandra[1]
[1]Department of Maritime Security, Faculty of National Security, Indonesia Defense University, Bogor, West Java, 16810, Indonesia
Asep Iwa Soemantri[2]
[2]Department of Maritime Security, Faculty of National Security, Indonesia Defense University, Bogor, West Java, 16810, Indonesia
Anwar Kurniadi[3]
[3]Department of Maritime Security, Faculty of National Security, Indonesia Defense University, Bogor, West Java, 16810, Indonesia

Corresponding Author: yosyea.oktaviandra@kn.idu.ac.id

Abstract

The Strait of Malacca is one of the world's most critical maritime routes, serving as a key conduit between the Indian and Pacific Oceans. However, this strategic corridor faces increasing threats from extreme weather events such as tropical storms, heavy rainfall, and high waves driven by climate change. These conditions severely limit the effectiveness of traditional maritime surveillance systems that rely heavily on radar and satellite technologies, which often fail under adverse weather. This study proposes the concept of a Resilient Surveillance Architecture (RSA) an adaptive monitoring system that integrates advanced radar, high-resolution satellite sensors, and drones equipped with infrared and miniaturized radar technology. RSA enhances real-time detection and monitoring accuracy, even under extreme weather conditions. Beyond technology, the study emphasizes the importance of climate-adaptive defense policies and international cooperation among littoral states such as Indonesia, Malaysia, and Singapore to strengthen the resilience of maritime surveillance systems. RSA is presented as a strategic solution to ensure navigational safety, bolster regional maritime security, and maintain the continuity of global trade in increasingly climate-vulnerable environments

Keywords: Strait Of Malacca, Maritime Surveillance, Extreme Weather, Resilient Surveillance

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Architecture, Drones, Climate Adaptation.

INTRODUCTION

The Strait of Malacca is one of the world's busiest shipping lanes, connecting the Indian Ocean with the Pacific Ocean. Approximately one-fifth of total global trade passes through this route, making it a strategic hub for the global economy (Jones et al., 2022). The Strait of Malacca plays a vital role in supporting international trade, energy distribution, and the supply of essential goods to various parts of the world. Therefore, maintaining the smooth operation of shipping through this strait is crucial, not only for countries directly bordering it, such as Indonesia, Malaysia, and Singapore, but also for the global economy as a whole.

However, despite its vital role, the Strait of Malacca faces increasing challenges due to more frequent extreme weather events. Extreme weather phenomena such as tropical cyclones, high waves, and extreme temperatures caused by climate change can disrupt shipping operations and affect the safety of ships transiting this area (Kendon et al., 2019). Intensifying climate change is impacting the stability of this shipping lane and increasing its vulnerability to disruptions that could harm the global economy. Research by Raymond et al. (2020) indicate that extreme weather in this region is expected to become more frequent, potentially threatening the safety and stability of this important international shipping lane.

In this context, the existence of an effective maritime surveillance system is crucial to ensuring the smooth and secure operation of the Strait of Malacca. Existing surveillance systems typically rely on radar, satellite, and drone technology to monitor vessel activity and detect potential threats along shipping routes. However, while these technologies have proven effective under normal weather conditions, they often struggle to provide accurate data during extreme weather (Jones et al., 2022). One major obstacle is the limited ability of radar to detect objects or vessels during heavy rain, tropical storms, or high waves.

Maritime radar, the primary technology used in surveillance, relies on electromagnetic waves that are susceptible to atmospheric interference, reducing their effectiveness under adverse weather conditions (Liu et al., 2020). For example, radar waves can be obscured by heavy rain or strong winds during tropical storms. Similarly, while satellites can provide useful data on sea conditions and vessels transiting the Strait of Malacca, they can only function optimally under relatively stable weather conditions (Vogel et al., 2019). When dense clouds or storms obstruct satellite visibility, the resulting image quality is reduced, significantly limiting real-time monitoring.

These challenges stemming from the limitations of radar and satellites create an urgent

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need for more robust surveillance systems that can operate effectively even in extreme weather conditions. Research by Kendon et al. (2019) emphasizes that maritime surveillance systems need to adapt to climate change, which increases the frequency and intensity of extreme weather events. Therefore, more innovative approaches are needed to address these challenges.

Therefore, this study proposes the use of Resilient Surveillance Architecture (RSA) as a solution to address the challenges faced by maritime surveillance systems in the Strait of Malacca. RSA integrates various advanced surveillance technologies, including advanced radar, satellites with advanced sensors, and drones, to create a surveillance system that is more flexible and responsive to extreme weather (Fazhan et al., 2020). The RSA offers a more adaptive approach that can strengthen the resilience of maritime surveillance systems in the Strait of Malacca to disruptions caused by increasingly frequent extreme weather.

The RSA optimizes the use of drones as a key element in maritime surveillance. Drones can operate at low altitudes and provide more detailed monitoring, even in adverse weather conditions that block radar or satellites. Research by Liu et al. (2020) shows that the use of drones in maritime surveillance can improve the accuracy of object and threat detection, as well as provide faster and more accurate data, even in less than ideal weather conditions. Drones are equipped with various advanced sensors, such as infrared sensors and miniaturized radars, which enable them to detect objects more precisely, even in very limited visibility.

In addition to drones, more sensitive advanced radars can also improve the resilience of surveillance systems in the face of extreme weather. According to research by Liu et al. (2020), advanced radars can perform better even in Heavy rain or tropical storms provide more accurate detection of objects in adverse weather conditions. Furthermore, satellites with advanced sensors can provide more complete and clearer data, even when severe weather obscures radar visibility (Vogel et al., 2019). The latest satellite technology allows for higher-resolution imagery, enhancing detection and monitoring capabilities in maritime areas affected by extreme weather.

The RSA relies not only on technology but also on climate adaptation-based defense policies. As extreme weather events increase due to climate change, climate adaptation-based defense policies are crucial to ensure that surveillance systems can function optimally in the face of changing weather conditions (Evers & Gerke, 2006). These policies include continuous technology development and updates, as well as increased operational capacity to address the growing impacts of climate change. Research by Raymond et al. (2020) shows that appropriate climate adaptation policies can increase the resilience of countries bordering the Strait of Malacca to extreme weather disturbances.

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Furthermore, the RSA proposes increased international cooperation between countries in the region. Collaboration between Indonesia, Malaysia, and Singapore is crucial for developing and implementing a surveillance system based on advanced technology (Kendon et al., 2019). These countries have a significant strategic interest in maintaining the smooth operation of the Strait of Malacca. Closer international cooperation will enable the exchange of technology and knowledge, which in turn will strengthen the resilience of maritime surveillance in the region.

The Resilient Surveillance Architecture (RSA) also offers a more resilient and sustainable long-term solution to address the increasingly frequent extreme weather events. The development of an RSA that integrates radar, satellites, and drones will enhance the capacity to detect, monitor, and respond to threats arising from extreme weather and other natural phenomena. In this regard, the RSA not only enhances the effectiveness of maritime surveillance but also strengthens a climate adaptation-based defense policy that is more flexible and responsive to ongoing changes.

As extreme weather events triggered by climate change become more frequent, a Resilient Surveillance Architecture (RSA) will be a critical component in strengthening the maritime surveillance system in the Strait of Malacca. The RSA, which includes the use of the latest technology and is supported by a climate-adaptive defense policy, will enhance the resilience of the maritime surveillance system and ensure smooth navigation through the Strait of Malacca.

METHODS

This research employs a qualitative-descriptive methodology rooted in conceptual and strategic analysis. The study aims to evaluate the vulnerabilities of traditional maritime surveillance systems in the Strait of Malacca under extreme weather scenarios and propose an integrated model known as Resilient Surveillance Architecture (RSA). The methodological design is structured in four stages:

Literature-Based Data Collection

The study relies entirely on secondary data from a broad spectrum of sources, including:

- Peer-reviewed journals in maritime security, climate science, and technology studies;
- International reports from IMO, WMO, and regional maritime agencies;
- Government policy documents concerning defense adaptation and climate resilience;
- Technical papers and case studies focusing on the integration of drones, radar, and satellite technologies.

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A total of over 30 scholarly and institutional references were analyzed to ensure relevance, reliability, and multidimensional insights.

Analytical Framework

The analysis is guided by a comparative approach examining:

- Operational limits of current maritime surveillance systems in adverse weather;
- Technological specifications and adaptability of drones, advanced radar, and satellite sensors;
- Case-based vulnerabilities in the Strait of Malacca;
- Climate adaptation policy models and international cooperative frameworks in maritime defense.

Conceptual Modeling

A conceptual model of Resilient Surveillance Architecture (RSA) was developed by integrating:

- Multi-sensor input systems (drones, radar, satellite),
- Real-time communication and decision-support mechanisms,
- Institutional and policy layers addressing climate threats and interoperability.

This model serves as a strategic framework for future implementation in Southeast Asia's critical maritime chokepoints.

Evaluation and Policy Recommendation

The study concludes by evaluating the effectiveness of RSA in enhancing:

- Maritime situational awareness,
- Rapid threat detection during extreme weather,
- Cross-border maritime cooperation,
- Climate-adaptive maritime security governance.

Policy recommendations are formulated to support joint operational readiness among littoral states Indonesia, Malaysia, and Singapore.

RESULTS AND DISCUSSION

Limitations of Conventional Maritime Surveillance Systems

The study reveals that current maritime surveillance systems operating in the Strait of

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Malacca primarily radar and satellite-based technologies face significant limitations under extreme weather conditions. Radar systems, which rely on electromagnetic waves, are particularly vulnerable to heavy rain, high winds, and atmospheric disturbances. As supported by Liu et al. (2020), traditional radar experiences signal degradation in storm environments, reducing detection accuracy. Similarly, satellite imaging suffers from decreased resolution and visibility during cloud cover and tropical cyclones (Vogel et al., 2019), limiting real-time situational awareness.

These limitations represent critical gaps in maritime security infrastructure, especially in one of the world's busiest sea lanes. As extreme weather events become more frequent due to climate change (Raymond et al., 2020), the need for resilient surveillance capabilities becomes urgent.

Effectiveness of Resilient Surveillance Architecture (RSA)

The proposed RSA model an integration of drones, advanced radar, high-resolution satellites, and climate-adaptive policy demonstrates a conceptual leap in maritime surveillance. This architecture offers multi-dimensional monitoring capability, addressing the weaknesses of each component system by reinforcing them through synergy:

- Drones provide close-range, low-altitude surveillance with the ability to operate in turbulent conditions. Equipped with infrared and miniaturized radar sensors, drones can capture real-time data and detect hidden threats even under poor visibility (Fazhan et al., 2020).
- Advanced radar systems with adaptive signal processing offer improved object detection during rainstorms and high sea states.
- Satellite sensors with multi-spectral capabilities contribute to macro-level monitoring, capturing ocean surface conditions and vessel movement data continuously, albeit supplemented by UAVs for granularity.

The RSA also introduces redundancy and interoperability, ensuring that if one component is compromised due to weather or technical failure, others can maintain operational continuity.

Strategic Relevance of Climate-Adaptive Defense Policy

Incorporating RSA into national maritime defense requires more than technological upgrades. The study emphasizes the strategic importance of climate-adaptive policies, which include:

- Periodic modernization of surveillance infrastructure;

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- Budget allocation for R&D in climate-resilient systems;
- Training for maritime personnel in extreme-weather response scenarios;
- Establishing protocols for rapid deployment of UAVs during environmental crises.

According to Evers & Gerke (2006), climate-aware defense strategy is key to long-term regional stability in maritime chokepoints like the Strait of Malacca. Without policy support, even advanced technology would face institutional and operational bottlenecks.

Role of Regional Cooperation

The results indicate that multilateral cooperation among Indonesia, Malaysia, and Singapore is essential for the successful deployment of RSA. Data sharing, joint drone operations, and coordinated response mechanisms would maximize the effectiveness of surveillance systems across the strait. Shared use of satellite data and interoperability protocols could reduce redundancy, increase cost-efficiency, and enhance real-time maritime domain awareness.

Jones et al. (2022) highlight that surveillance in a transboundary maritime corridor cannot rely solely on unilateral efforts. RSA must be embedded in a regional security framework supported by diplomatic and technical agreements.

CONCLUSIONS

The Strait of Malacca, a globally critical maritime chokepoint, faces increasing operational risks due to the rising frequency and intensity of extreme weather events brought on by climate change. Conventional surveillance systems relying predominantly on radar and satellites are no longer sufficient to ensure maritime security in such volatile environments. Their limitations under adverse weather underscore the urgent need for a more adaptive and integrated solution.

This study proposes the Resilient Surveillance Architecture (RSA) as a strategic framework that enhances maritime domain awareness and operational resilience. By integrating drones, advanced radar systems, and satellite technologies, RSA ensures redundancy, real-time data collection, and robust monitoring even under severe weather conditions. Furthermore, the system is supported by a climate-adaptive defense policy framework that emphasizes technological modernization, capacity building, and environmental preparedness.

Successful implementation of RSA, however, cannot be achieved through technology alone. Multilateral cooperation among Indonesia, Malaysia, and Singapore is essential to establish interoperable systems, share data efficiently, and develop joint response strategies. This collaboration not only addresses regional security needs but also strengthens global maritime

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trade resilience.

In conclusion, the Resilient Surveillance Architecture offers a comprehensive and forward-looking solution to safeguard the Strait of Malacca. It combines technological innovation with strategic policymaking and regional diplomacy, positioning maritime surveillance systems to meet the challenges of an increasingly unpredictable climate. RSA thus serves as a vital model for future-oriented maritime security frameworks in climate-sensitive and geopolitically significant regions worldwide.

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