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Detection Of The Thermal Front Using The Cayula-Cornillon Alghorithm: A Case Study Of The State Fisheries Management Area 713, Indonesia

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ABSTRACT

Thermal fronts are pivotal in shaping the marine ecosystem, influencing the presence and distribution of marine species. This study delves into the fluctuating patterns of thermal fronts in Indonesian waters, specifically focusing on the State Fisheries Management Area of the Republic of Indonesia, known as WPPNRI, 713. We identified the distribution and frequency of thermal fronts across different monsoon seasons. Utilizing the extended Cayula Cornillon Algorithm – Single Image Edge Detection (CCA-SIED), we deploy a precise methodology for detecting these fronts, relying on sea surface temperature (SST) gradients to identify specific periods and regions. Our analysis encompasses extensive satellite data collected from Moderate Resolution Imaging Spectroradiometer (MODIS) level 3. Our findings unveil distinct seasonal variations, with a decrease in thermal fronts during the west monsoon and a surge during the east monsoon. Moreover, we identify regional disparities, with denser thermal fronts observed in the southern and middle regions compared to the northern areas. Furthermore, our study underscores the critical need to integrate oceanographic data with fisheries management strategies to address the impacts of climate variability on marine resources. The observed relationships between thermal fronts, nutrient distribution, and fish migration emphasize the necessity for ongoing, localized monitoring to develop adaptive management solutions. This research marks a significant step in characterizing thermal fronts in WPPNRI 713, laying the groundwork for future investigations into other ecologically significant fronts, including those related to chlorophyll, salinity, and nutrients, thereby enhancing our understanding of marine ecosystem dynamics.

INTRODUCTION

The world ocean consists of water loads separated from the resources of fronts. The front is a slim transition between two adjoining marine ecosystems (Louzao et al., 2017). Each of these ecosystems inhabits an exquisite water mass characterized by the ability to an exclusive mixture of temperature, salinity, nutrients, and microelements (Puthezhath, 2014). Fronts impact a range of elements of the ecology of marine animals migrations, foraging, reproduction, recruitment, and connectivity. The results of a Belkin (2021) study of more than 80 marine and fisheries ecology articles indicate an increase in biomass and biodiversity at or near the front.

Marine fisheries are a vital monetary quarter and assist in meeting a country's dietary needs. However, they are under stress because of overexploitation

(Ababouch and Carolu, 2015). One strategy to tackle this is to direct the fleet to areas of greater productivity (Mohanty et al., 2017). However, to obtain this, it's critical to look at the marine surroundings over many seasons to increase in-depth knowledge of the elements that affect productivity and map regions that remain productive.

Based on the Regulation of the Minister of Marine Affairs and Fisheries of Indonesia Number 18/Permen-KP/2014 concerning the State Fisheries Management Area of the Republic of Indonesia (called WPPNRI), it is divided into 11 zones (Republik Indonesia MK dan P, 2014). Each zone has different ecosystem characteristics and potential. The WPPNRI is the basis for the Indonesian fisheries governance (Damanik & Lubis, 2016). One is WPPNRI 713, which covers the waters of the Makassar Strait, Bone Bay, Flores Sea, and the Bali Sea as a place to catch fish for fishermen.

The boundary between Sea Surface Temperature (SST) zones, where heat water can cross vertically or horizontally, is where an oceanic thermal front has formed (Mohanty et al., 2017; Sun et al., 2022). Because the thermal front represents a convergence of water masses with various characteristics that can concentrate planktonic particles and increase productivity (Kahru et al., 2018; Sholva et al., 2013; Zhang et al., 2019), ocean fronts can be crucial in establishing favourable spawning circumstances (Nieblas et al., 2014). For foraging, reproduction, recruitment, and migration, fish seek out such oceanic features (fronts and eddies) as habitats of preference (Kahru et al., 2018). Garcés-Rodríguez et al. (2021) describe an increase in zooplankton abundance and biodiversity in the surface mixing layer of the stratified side of the front. The front served as a feeding location for many pelagic species, including many megafauna species (Narcisse et al., 2020).

The user needs the information point coordinates of the Potential Fishing Zones (PFZ) to execute fishing operations more successfully. The Institute for Marine Research and Observation Indonesia (IMRO) has regularly produced maps of fishing zones since its establishment in 2005. The maps were initially created manually and only used fundamental techniques that took a long time. However, many methods and processes have been developed by utilizing technology to determine PFZ. IMRO tried to integrate a Python-based script that automatically evaluates the potential size of the fishing zones (Ardianto et al., 2017). Fitrianah et al. (2016) examined how a data mining method for determining possible fishing zones uses the AGRID+ algorithm, a density grid-based grouping for high dimensional data. In fisheries management with an Ecosystem Approach to Fisheries Management (EAFM), image analysis is used to consider the habitat and population dynamics of marine fish, one of which is the Moderate Resolution Imaging Spectroradiometer (Hamzah et al., 2016).

The manual identification of frontal gradients is a complicated (Zhang et al., 2019) and inaccurate task. Due to high ambiguity brought on by human error, manual front identification typically relies on visual judgment. The most applicable method to detect the front of the SST image automatically is by utilizing a geographic information system as a processing algorithm, one of which is edge detection (Belkin and O'Reilly, 2009). Edge detection was the approach used to create the automated processing system. This technique could spot thermal fronts that could be signs of many oceanographic phenomena, including upwelling fronts, frontal eddies, and fronts connected to geomorphic characteristics (Ardianto et al., 2017).

The Cayula-Cornillon Algorithm (CCA), developed by Jean-François Cayula and Peter Cornillon, is the most sophisticated edge recognition method used in early satellite oceanography for SST images. Single-image edge detectors (SIED) and multi-image edge detectors for the CCA are available (Belkin, 2021). The SIED method detects the thermal front in sea surface temperature data. The SIED method used for automatically processing front information is the SIED algorithm, which has been implemented in ArcGIS software into a toolbox incorporated into the Marine Geospatial Ecology Tools (MGET) application (Roberts et al., 2010).

The PFZ can be estimated by looking at the thermal gradient/front shift detected in the image. Much research on determining fishing areas, including front analysis, has been carried out (Hamzah et al., 2016) to determine the coordinate point/geometric centre of the identified sea surface temperature thermal front for the pelagic fishing potential zone. Nieblas et al. (2014) Found the front activity and its relationship to ocean dynamics and surface features of the tropical southeast Indian Ocean for bluefin tuna spawning grounds. Suhadha & Asriningrum (2020) Tested the accuracy of the thermal front to predict PFZ in WPPNRI 715 on mesotrophic. They found that the suitability between the thermal front and mesotrophic area for PFZ was 60% for January–December 2018 (acceptable because it was more than 50%). The thermal front is the main parameter in the PFZ information input of the National Institute of Aeronautics and Space (LAPAN Indonesia). However, the distribution and frequency of thermal fronts based on seasons need to be analyzed for several years so that they can be used to predict the potential for fishery zones (PFZ) with high productivity. Because of the weather conditions affecting certain waters, marine features change in intensity and distribution on a spatial and temporal basis (Yusuf et al., 2022).

Thermal fronts play a crucial role in the marine ecosystem, influencing the abundance and distribution of marine Species. While previous studies have examined the general impact of thermal fronts on marine ecology, there has been limited focus on their seasonal variations and specific regional characteristics. This research addresses this gap by analyzing the distribution and frequency of thermal fronts in the State Fisheries Management Area of the Republic of Indonesia (WPPNRI 713) across different monsoon seasons. We provide more precise identification of thermal fronts by utilizing satellite images of sea surface temperature (SST) and extending the Cayula Cornillon Algorithm - Single Image Edge Detection (CCA-SIED). This study enhances our understanding of thermal front dynamics in Indonesian waters and offers practical insights for optimizing fishing zones, thereby contributing to sustainable fisheries management. Science-based technology in fishing can still go hand in hand with local wisdom (Puspitawati & Pei Ze, 2023). By integrating advanced remote sensing techniques and methodological innovations, our research provides a novel perspective on thermal fronts' temporal and spatial variability and their implications for marine ecology and fisheries.

RESEARCH METHODS

The WPPNRI oversees fishing, fish farming, conservation, study, and fishery enhancement (Republik Indonesia MK dan P, 2014). The main focus of this study area is in WPPNRI 713, which covers the Indonesian waters of the Makassar Strait, Bone Bay, Flores Sea, and the Bali Sea (Figure 1).

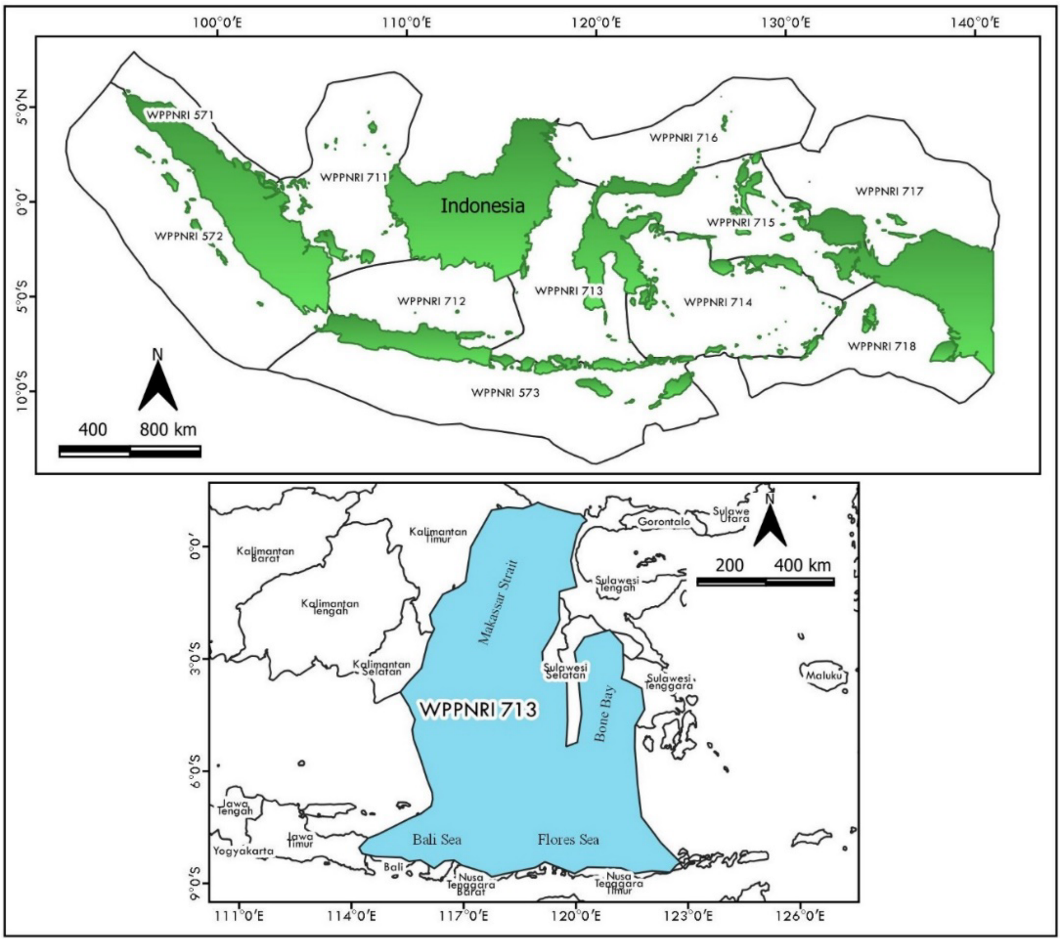

Figure 1. The States Fisheries Management Area Indonesia 713 (Sources: Statistics Indonesia of Berau, 2023).

Multitemporal analysis of surface temperature can predict the area of fish catch in the sea (Zahrotunisa et al., 2022), through remote sensing images the analysis is easy and efficient to do with the help of GIS (Sukri et al., 2023). In this study, Sea Surface Temperature (SST) images were downloaded from Nasa Ocean Color. We used five years of data from Moderate Resolution Imaging Spectroradiometer (MODIS) level 3 with a monthly period and resolution of 4 km from 2017 to 2021 to detect the thermal front. Initial data processing, such as geometry correction and clipping, is done before the thermal front detection.

Usually, one method that uses satellite data is used to find the front, namely the gradient-based algorithm. The SST detection algorithm deals with edge detection and operates at three levels: picture, window, and local-pixel levels (Narcisse et al., 2020). That algorithm looks for the horizontal gradient in the ocean, such as a temperature, using the convolution operator. In a population-based technique, a histogram shows the separation of two bodies of water.

This technique is applied in GIS using the Cayula Cornillon Algorithm - Single Image Edge Detection (CCA-SIED) approach (Cayula and Cornillon, 1992). This method tests histograms created from separate image subwindows for bimodality to identify two water masses with different attributes. This process also gives the value that bisects the histogram and defines the front that separates the two water masses. Using pixels at this value, a contour following method generates spatially explicit edges for the subwindow (Nieblas et al., 2014).

In this study, CCA-SIED was applied using the Open-source Marine Geospatial Ecology Tools (MGET) to detect thermal fronts in data in Terra-MODIS level 3 in

ArcGIS 10.4. Detections are carried out to see the distribution, frequency, intensity, and persistence of the thermal front based on seasons, which can be used to determine the potential for zone fisheries (PFZ) with high productivity. Locations with high density, intensity, and persistent thermal fronts can be suitable for PFZ. The research framework is shown in Figure 2.

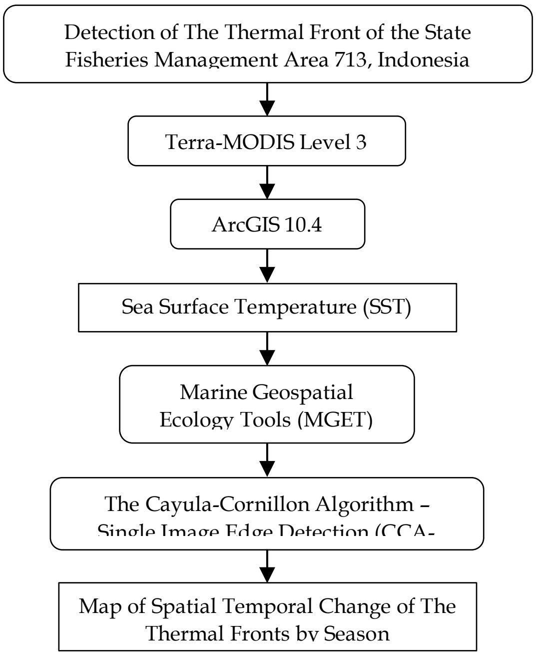

Figure 2. Research Framework (Sources: Tjasyono et al., 2008)

Regarding geography, fronts are essentially the dividing lines between two populations of pixels that reflect a bimodal histogram distribution in an image. The front of SST is a line between two distinct populations of pixels that represent sea masses with different temperatures. The gradient, or separation between two modes in SST, determines how strong the front's boundary will be. The greater the variance between the mean values of the populations, the greater the gradient of the fronts. The SST gradient values were assigned as one is front and zero is no front. Based on this, a semi-automated synthesis tool employing ArcGIS functions was created to eliminate all noise and split thermal fronts into lines. Further investigation was conducted using these lines that represented the thermal fronts.

Each month's total number of front pixels is plotted by monsoon against various SST gradient levels. The season period used is divided into four periods because the study area is in the southern hemisphere of Indonesia (Table 1).

Table 1. Classification of the season in terms of the monsoon in Indonesia

The Monsoon		Period
Northern hemisphere	Southern hemisphere	
Northeast monsoon	West monsoon	December – January - February
First transition	First transition	March – April - May
Southwest monsoon	East monsoon	June – July - August
Second transition	Second transition	September – October - November

RESULTS AND DISCUSSION

Our study reveals significant seasonal variation in thermal front occurrences within the WPPNRI 713. Thermal front detection is critical to look at spotting high-productivity water areas. We detect thermal fronts based on monsoons using CCA-SIED. The detection results were contour-like lines consisting of red, blue, and green (Figure 3). This line indicates the meeting location of two seawater masses with different temperatures, suspected as the front. The monsoon thermal front distribution comparison in WPPNRI 713 from 2017 to 2021 (Table 2).

Table 2. The comparison of monsoon thermal front distribution from 2017 to 2021.

Season	Area	Comparison of the thermal front
The west monsoon	North Middle South	A lower frequency, intensity, and persistency in all areas
The first transition	North Middle South	A narrow distribution, with a fairly long size and more consistent in the south than in the middle and north
The east monsoon	North Middle South	More concentrated and consistent in the south and middle than in the north by having a long size
The second transition	North Middle South	A wide distribution, varying in size and consistent, in the south rather than in the middle and north

(Sources: Research Results, 2023)

The thermal front has seasonal variations. During the western monsoon, only a few thermal fronts are detected yearly with low intensity and persistent every year except 2021. The thermal front is consistent yearly in february, while in December and January, it only formed in 2019. During the first transition period, the thermal fronts began to increase but were still few, with a fairly long size and more consistently formed thermal fronts in the south than in the middle and north every year. The thermal front consistently appears in April and May every year, but it did not form in March in 2017 or 2018 and will not be formed again.

More thermal fronts are formed in the eastern monsoon than in the previous seasons with higher intensity. The thermal front in this season is consistently formed every year and is concentrated in the south (center of the study area). The second transition period, the thermal front, decreased in number compared with the east monsoon but more than the west monsoon and the first transition. Thermal fronts are spread out with varying and consistent intensity in the south rather than in the middle and north. A thermal front is formed annually in October, while September and November are inconsistent. Our findings reveal distinct seasonal patterns, with fewer thermal fronts detected during the west monsoon and a higher density during the east monsoon. Furthermore, we observe a regional disparity, with denser thermal fronts in the southern and middle regions compared to the northern counterparts.

The findings of this study show notable differences from previous research, particularly in the timing and intensity of thermal front formation. For instance, (Suhadha & Asriningrum, 2020) identified December as the peak month for thermal fronts in WPPNRI 715, contrasting with our observations in WPPNRI 713, where December and January show less consistent formation. These discrepancies underscore the regional variability of thermal front dynamics and suggest that local factors, such as currents, wind patterns, and topography, may play significant roles. This difference highlights the importance of region-specific studies. Local oceanographic features, such as the interaction of currents and wind patterns, can lead to significant variations in thermal front dynamics. By comparing multiple regions, researchers can better understand the factors influencing thermal front formation and their ecological implications.

The thermal front is extracted from the SST while many factors, including sunlight, the geographic location of the waters, current circulation, sea depth, wind, and seasons, influence the SST distribution. Fluctuating sea surface temperatures are influenced by surface current circulation (Obenour, 2013). The wind causes the circulation of ocean surface currents. Sea surface temperatures vary spatially and temporally, and the influencing factors are very complex. However, in the waters of the Indonesian Archipelago, the dominant influencing factors are local monsoons and the mixing of water masses due to tides (Yusuf et al., 2022b). In the study area, the distribution of sea surface temperature varies, with high intensity dominant in the northern part (Makassar Strait) and eastern part (Bone Bay). In contrast, the southern part (Flores Sea) has a lower temperature (Yusuf et al., 2022a).

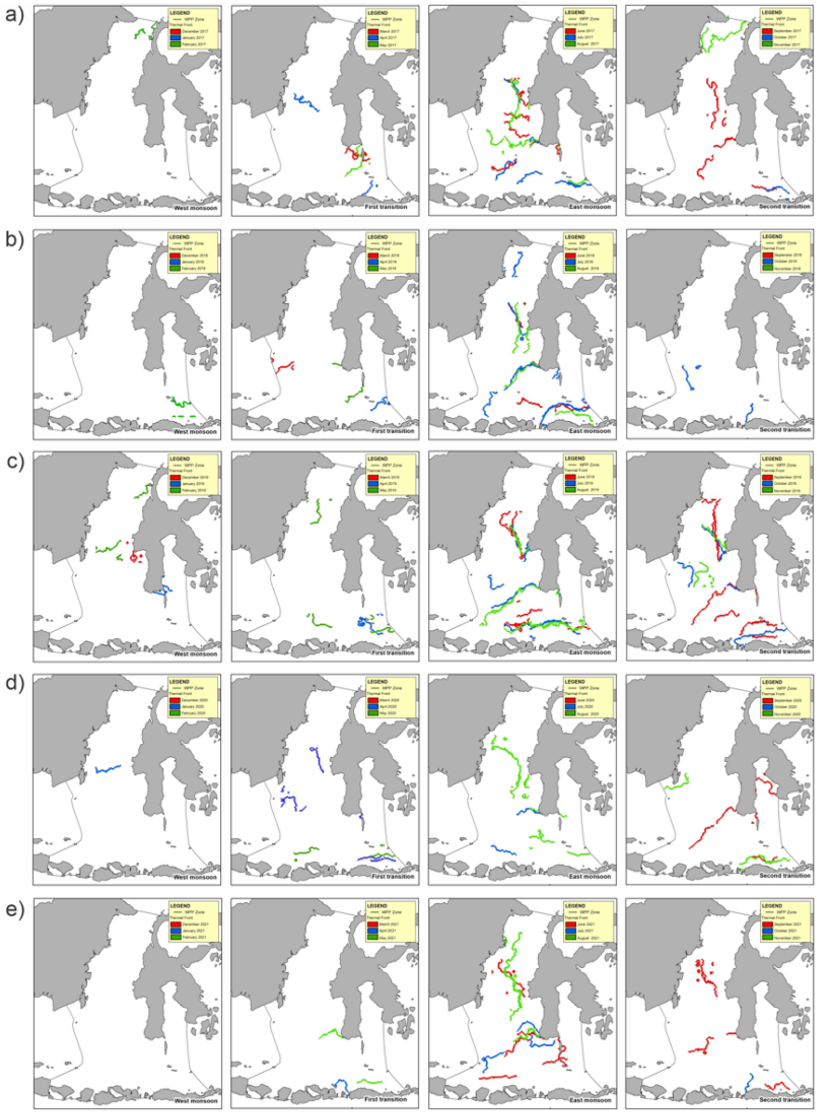

Figure 3. The distribution of thermal front in WPPNRI 713 is based on monsoons. The left column is for the west monsoon, the second is for the first transition, the third is for the east monsoon, and the right is for the second transition. a) The top row is for 2017; b) The second row is for 2018; c) the third row is for 2019; d) The fourth row is for 2020; e) The bottom row is for 2021 (Sources: Research Results, 2023).

Seasonal cycles, driven by the variability of climatic factors, play a crucial role in determining the patterns of thermal fronts and the associated marine productivity. These cycles manifest as predictable, cyclical changes in environmental conditions that significantly influence the distribution and abundance of marine life (Poloczanska et al., 2016). Based on research (Mohanty et al., 2017) in the northeast Arabian Peninsula, they discovered a strong coherence of thermal front density with high chlorophyll concentrations, with high front density in the northern areas during the autumn and in the southern parts during the winter period. This pattern was associated with an increase in primary productivity approximately four weeks after the peak in thermal front density. This time-lag effect suggests that the formation of thermal fronts can be a precursor to increased biological productivity, offering a valuable tool for forecasting high-productivity periods.

Understanding thermal fronts' seasonal and spatial dynamics is crucial for fisheries management. Thermal fronts often coincide with nutrient-rich areas that attract fish, making them important for determining fishing grounds. This is related to fish migration and the availability of nutrients in a region (Worthington et al., 2022). The potential zone for catching large pelagic fish in WPPNRI 713 differs from what Safruddin et al. (2019) found, especially in Bone Bay, which is formed from April to September, with the peak season occurring in May every year. Large pelagic fish begin to migrate from February to March to the Bone Bay area, whereas large pelagic fish migrate out from October to January. Meanwhile, in this study, it seems that June-November in Bone Bay has the potential for fishing, with October as the peak. It is because, during that month, a thermal front is formed in the northern part of Bone Bay, so fish are likely to migrate in until October.

This discrepancy can be attributed to the formation of a thermal front in the northern part of Bone Bay during October, which likely attracts fish to the area until the end of the month. These findings highlight the importance of localized studies and continuous monitoring to identify and predict optimal fishing periods accurately. The identification of seasonal patterns in thermal front formation and fish migration can significantly enhance fishing strategies (Reese et al., 2011). By aligning fishing efforts with the periods when thermal fronts are most likely to form, fisheries can optimize their catch rates, ensuring better yields and more efficient resource use. The discrepancies observed between our study underscore the need for region-specific fishing calendars that reflect localized environmental conditions.

In addition, the study of seasonal cycles and their impact on marine productivity is crucial for informing and broader climate adaptation strategies. Global warming, wind systems, and seasonal movement improperly cause extreme climate changes (Kurniawan, 2017; Susilawati et al., 2024). As climate change continues to alter oceanographic conditions, a detailed understanding of these changes' effects on thermal front formation and biological productivity becomes essential (Franco et al., 2020). Such insights are vital for developing adaptive management practices to mitigate climate variability's impacts on marine resources. By comprehending thermal fronts' temporal and spatial dynamics, we can gain critical insights into the optimal management of marine resources. Knowledge of the timing and locations of thermal front formation can guide the formulation of policies and regulations to sustain fish populations and their habitats (Cooke et al., 2023). Protecting areas during periods of peak productivity can thus ensure the long-term health and sustainability of marine ecosystems.

This research enhances our understanding of thermal fronts' temporal and spatial variability in Indonesian waters, specifically in WPPNRI 173. By identifying the periods and regions where thermal fronts are most prevalent, fisheries can optimize their efforts, improving catch efficiency and sustainability. The extended Cayula and Cornillon Algorithm - Single Image Edge Detection (CCA-SIED) employed in this study offers a more precise method for detecting thermal fronts, which can be utilized in other regions to advance marine ecological research. Additionally, the observed correlation between thermal fronts and potential fishing zones underscores the importance of integrating oceanographic data with fisheries management practices, ultimately contributing to the sustainable exploitation of marine resources.

The study of thermal fronts in WPPNRI 713 and their seasonal variations provides critical insights that can enhance fisheries management, resource sustainability, and climate adaptation strategies. Compared to previous research, the observed differences in thermal front patterns and fish migration highlight the importance of localized and continuous monitoring to predict and manage marine resources accurately. Future research should focus on integrating these findings into comprehensive management plans that consider regional specifics and broader climatic trends.

To our knowledge, this paper is the first to characterize the thermal fronts in the study area, which is a zone where conditions in the upper ocean are very variable and complicated by currents. By examining the sea surface temperature (SST) gradient's detected fronts, we can help characterize fishing zones. Our research demonstrates the complexity of the thermal front dynamics in WPPNRI 713, which encompasses the Makassar Strait, Bone Bay, Flores Sea, and Bali Sea. We offer numerous potential connections with regional and remote ocean dynamics. While our study focuses on thermal fronts, other ecologically significant front types, such as those involving chlorophyll, salinity, and nutrients, may also be prevalent. We recommend that future studies explore these additional fronts, crucial for a comprehensive understanding of the marine environment.

CONCLUSION

The study results of the thermal front seasonal distribution provide critical information for finding persistence with a high level of productivity that can act as PFZ. Our study shows a diverse incidence of thermal fronts in the WPPNRI 713. A high frequency of thermal fronts was detected during the east monsoon. Overall, the southern and central sections of the WPPNRI 713 showed a larger density of thermal fronts than their northern counterparts. We conclude that fishing might be possible in the high density of the thermal front area. Our findings might also be in favor of the high-productivity regions for fish. Validation is needed using user field data to determine and increase the resulting PFZ's accuracy. The study of thermal fronts in WPPNRI 713 and their seasonal variations provides critical insights that can enhance fisheries management, resource sustainability, and climate adaptation strategies. Future research should focus on integrating these findings into comprehensive management plans that consider regional specifics and broader climatic trends.

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