Satellite-derived Spatio-temporal Dynamics of Sea Surface Temperature in the Indonesian and Halmahera Seas During ENSO Events

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https://doi.org/10.5109/7342472

出版情報：Evergreen. 12 (1), pp.526-540, 2025-03. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
バージョン：

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(Received November 28, 2024; Revised January 24, 2025; Accepted February 19, 2025).

Abstract: Our study investigates the satellite-derived spatio-temporal dynamics of sea surface temperature (SST) in the Indonesian and Halmahera Seas from 2019 to 2021, highlighting its implications for climate change and marine resource management. SST values range from 21.95ºC to 33.50ºC, with pronounced peaks during the East Season (June to October) and lower temperatures in the West Season (January to March). These variations are closely associated with the El Niño-Southern Oscillation (ENSO) and seasonal wind and rainfall patterns. During the East Season, we observed notable upwelling events that indicate significant ecological impacts on fish distribution and fisheries productivity. Our study employed Conductivity-Temperature-Depth (CTD) data to validate satellite observations from the Copernicus Marine Environment Monitoring Service (CMEMS). The results revealed a strong correlation between satellite and observation data (coefficients of 0.91 and 0.93), confirming the reliability of satellite data for monitoring SST in remote marine areas. Our findings underscore the critical importance of continuous SST monitoring for sustainable marine resource management and the integration of satellite data in oceanographic studies. Our study is vital for developing adaptive strategies to address climate variability, particularly El Niño and La Niña events, which significantly influence regional weather patterns and ocean dynamics and ultimately impact global climate systems. Future research should explore the long-term trends of SST toward ongoing climate change and the resilience of marine ecosystems in the face of such variability.

Keywords: Sea Surface Temperature (SST); Indonesian and Halmahera seas; CTD; El Niño-Southern Oscillation (ENSO); climate change

1. Introduction

Indonesia, with its extensive maritime territory, plays a crucial role in global ocean dynamics and climate regulation. This region's interplay of physical oceanography and geological factors significantly influences climate change and natural disasters. The spatio-temporal variability of sea surface temperature (SST) in the Halmahera Sea, Indonesia, is an important phenomenon affecting marine ecosystems and fisheries activities. 2021 is a strong year for La Niña in Indonesian waters in ENSO events. Indonesia boasts a vast water area with physical oceanography and geological influences that can impact climate change and disasters[1–5]. Spatio-temporal variability of sea surface temperature (SST) in Halmahera Sea, Indonesia, is an important phenomenon affecting marine ecosystems and fisheries activities. Not only does fluctuating SST affect the life of marine biota, but it also bears a close relationship with global climate change[6].

Previous studies have shown that changes in SST can trigger changes in weather patterns and broader environmental conditions[7,8]. Satellite data enables more accurate and efficient SST analysis in Halmahera, offering more profound insights into the ocean dynamics in this region. The pattern of water mass movement affects the fluctuation of surface oceanography variables, such as sea surface temperature[9]. Sea surface temperature is a crucial oceanography parameter that enhances the quality of fishery resources. Khan et al. (2021) suggests using sea surface temperature as an indicator to estimate upwelling and downwelling locations[10].

Furthermore, changes in SST in the Halmahera Sea can affect fish migration patterns and fisheries productivity. Research conducted by Suniada, 2021 shows that temperature can affect food availability for certain fish species, which impacts the livelihoods of coastal communities[11]. Therefore, a better understanding of SST variability is essential to support the thirst for fisheries resources and the welfare of communities dependent on the sea[12]. In addition, research by Sepri et al. (2021) shows that changes in SST can cause habitat changes for commercial fish species, potentially reducing catches[13]. This emphasizes the importance of SST monitoring to formulate adaptive and sustainable fisheries management strategies[14].

Satellite SST monitoring allows for broader and more continuous observations compared to conventional methods. This is especially important considering the complexity of the interactions between ocean currents, temperature, and atmospheric conditions in tropical regions[15]. Furthermore, SST analysis can also provide important information about potential natural disasters, such as El Niño and La Niña, which are often triggered by changes in ocean temperature. Research by Leupold et al. (2021) emphasizes the importance of SST monitoring in predicting extreme events that can harm local ecosystems and economies[16]. Thus, a deeper understanding of SST in Halmahera is not only beneficial for academic research but also for better planning and policies for marine resource management. Utilizing Sea Surface Temperature (SST) as a primary variable is crucial due to its significant influence on weather patterns and climate variability, especially during El Niño-Southern Oscillation (ENSO) events. Variations in SST can profoundly affect marine ecosystem health and the livelihoods of communities reliant on marine resources. Additionally, advancements in satellite technology have granted unprecedented access to high-resolution SST data, facilitating detailed analyses of spatio-temporal dynamics. This integration of SST data is essential for understanding the complex interactions within marine environments and their responses to climatic changes.

Our study aims to analyze the spatio-temporal dynamics of sea surface temperature (SST) in the Indonesian and Halmahera Seas during 2019–2021 to provide critical insights for marine resource management and mitigate the impacts of climate change in Indonesia. By identifying distinct patterns of SST variability related to global climate phenomena such as El Niño and La Niña, we uncover their specific impacts on marine ecosystems in the Halmahera Sea. Our findings reveal significant shifts in fish species distribution and fisheries productivity in response to changing SST, highlighting the intricate relationship between SST and climate conditions. Our studies contribute novel insights into ecosystem dynamics, offering valuable information for stakeholders, including government agencies and fishing communities, to formulate effective adaptation strategies against climate change. Furthermore, we anticipate the results will enrich the existing scientific literature, underscoring the critical importance of continuous SST monitoring in Indonesia's sustainable marine resource management, particularly during ENSO events.

2. Data and Method

2.1 Study sites

Figure 1 shows that our study site is in the Indonesian Sea, with coordinate limits of longitude 95°E to 141°E and latitude 11.6°S to 6°N. This region is characterized by complex oceanographic features, including strong currents and diverse thermal stratification, significantly influencing local marine biodiversity. Additionally, the Indonesian Sea is a critical junction for exchanging water masses between the Pacific and Indian Oceans, making it pivotal for understanding broader oceanic and climate processes[14].

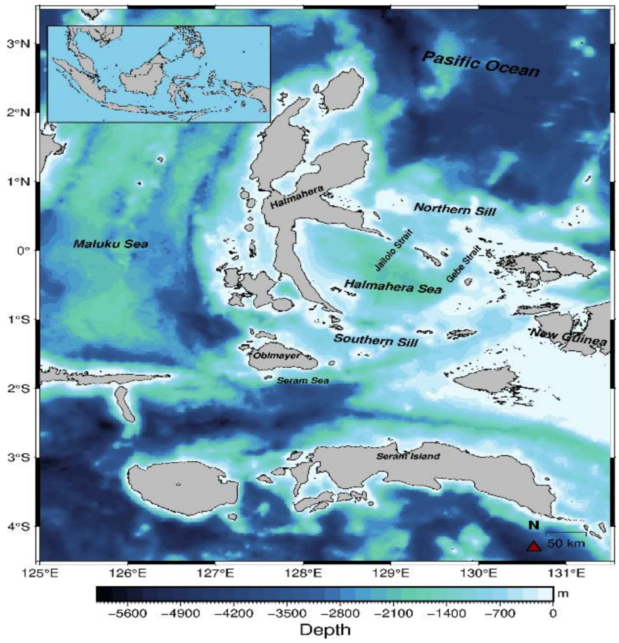


Fig. 1: Location of the Indonesian: Halmahera Sea provided from PyGMT relief with a resolution of 1m.

2.2 Data collection and analysis

In our study, we collected and analyzed data from the Global Ocean Physics Reanalysis to understand sea surface temperature dynamics (SST) in the Indonesian and Halmahera Seas from 2019 to 2021. The findings from this analysis aim to provide deeper insights into SST variability and its implications for marine ecosystems in the region. The data collection from Global Ocean Physics Reanalysis has a spatial resolution of 0.083° × 0.083°. The GLORYS12V1 package consists of data collected from the CMEMS global ocean eddy-resolving reanalysis, including altimetry data from 1993 onward (https://doi.org/10.48670/moi-00021). This product comprises daily and monthly mean files for temperature, salinity, currents, sea level, mixed layer depth, and ice characteristics from the surface to the seabed. A regular grid presents the worldwide ocean output files at a resolution 1/12°. We utilized the product ID GLOBAL_MULTIYEAR_PHY_001_030, which is associated with the variable seawater potential temperature (T)[17]. We generated the resultant graphics utilizing Python version 3.11, detailing the research site and modifying requirements for Indonesia and the Halmahera Sea (HS) from 2019 to 2021.

The data analysis indicated that La Niña conditions were predominantly present in 2020–2021, marked by negative sea surface temperature anomalies in the Niño 3.4 region, leading to cooler ocean temperatures and significant alterations in atmospheric circulation patterns. While brief periods of neutral or weak El Niño conditions occurred, they were not dominant. The method involved looking at SST data from satellites along with outputs from climate models to understand how La Niña events change over time and how they affect weather patterns around the world and in different regions.

Our study examined the fluctuations of sea surface temperature (SST) values from 2019 to 2021. The results will also display a temporal distribution pattern. We evaluate these data by assessing the correlation coefficient, root mean square deviation (RMSD), and standard deviation utilizing the Taylor Diagram, which illustrates the extent of annual variability of sea surface temperature (SST) in the Indonesian and Halmahera Seas[18].

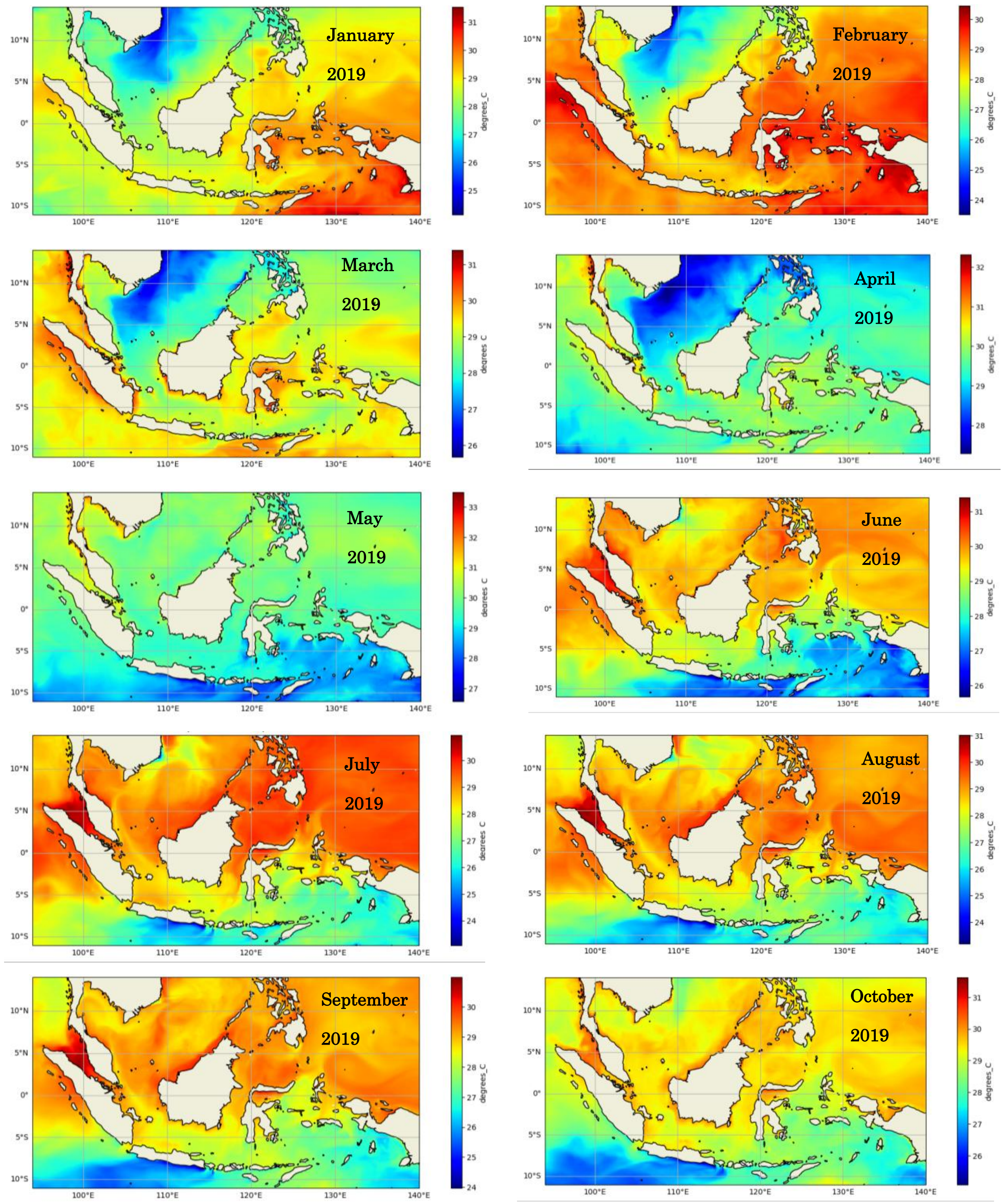
The RMSD offers significant insight into the magnitude of the anticipated error of the employed model when examining the annual variability of SST in the Indonesian and Halmahera Seas. Our study uses observation data from the JALA CITRA 1 “AURORA” Expedition, 2021). Two data collection stations use this data to validate SST data at each depth until 500 m. Station 1 is located at 0.72°S, 129.27°E, and Station 2 is at 0.52033°S, 129.27°E.

We focused on validating satellite data from CMEMS using two observation points, confirming its suitability for our research. Our research indicates that we can use CMEMS data with a 1/12 resolution to examine SST in the Halmahera Sea (HS) area. We used data from 2021 for our validation; it shows how important it is to compare satellite measurements with field data and CTD data from observations to make SST estimates more accurate in the HS.

3. Result and Discussion

3.1. Variability of SST in the Indonesian and Halmahera Seas in 2019

The distribution of SST concentration values in the Indonesian Sea during January-December 2019 ranged from 23.35-33.13ºC. Figure 2 presents the spatial distribution of SST values. The distribution of SST values in 2019 experienced the highest SST peaks in the East Season (June, July, August, and September) and the West Season (January, February, and March). The interaction between the ENSO phenomenon and seasonal wind and rainfall patterns can be associated with the highest SST peaks during the East Season (June to September) and lower SST in the West Season (January to March)[19]. The lowest decrease in SST variability reached 28.70°C. The SST value in the 2019 East Season ranged from 23.56 to 26.49ºC. The low SST value compared to other seasons indicates an upwelling phenomenon in the Indonesian sea.



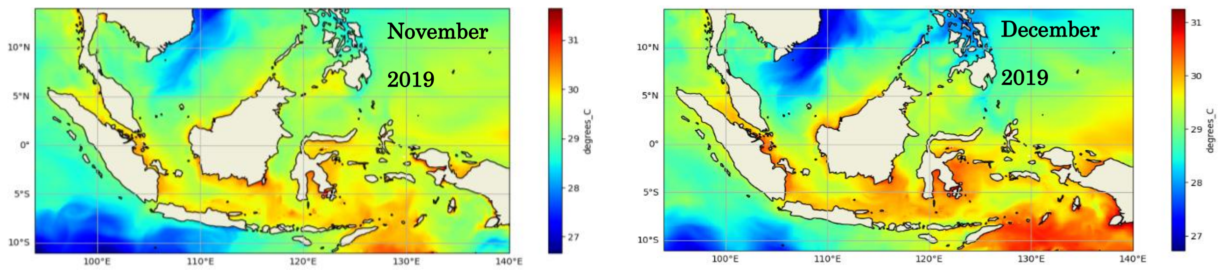
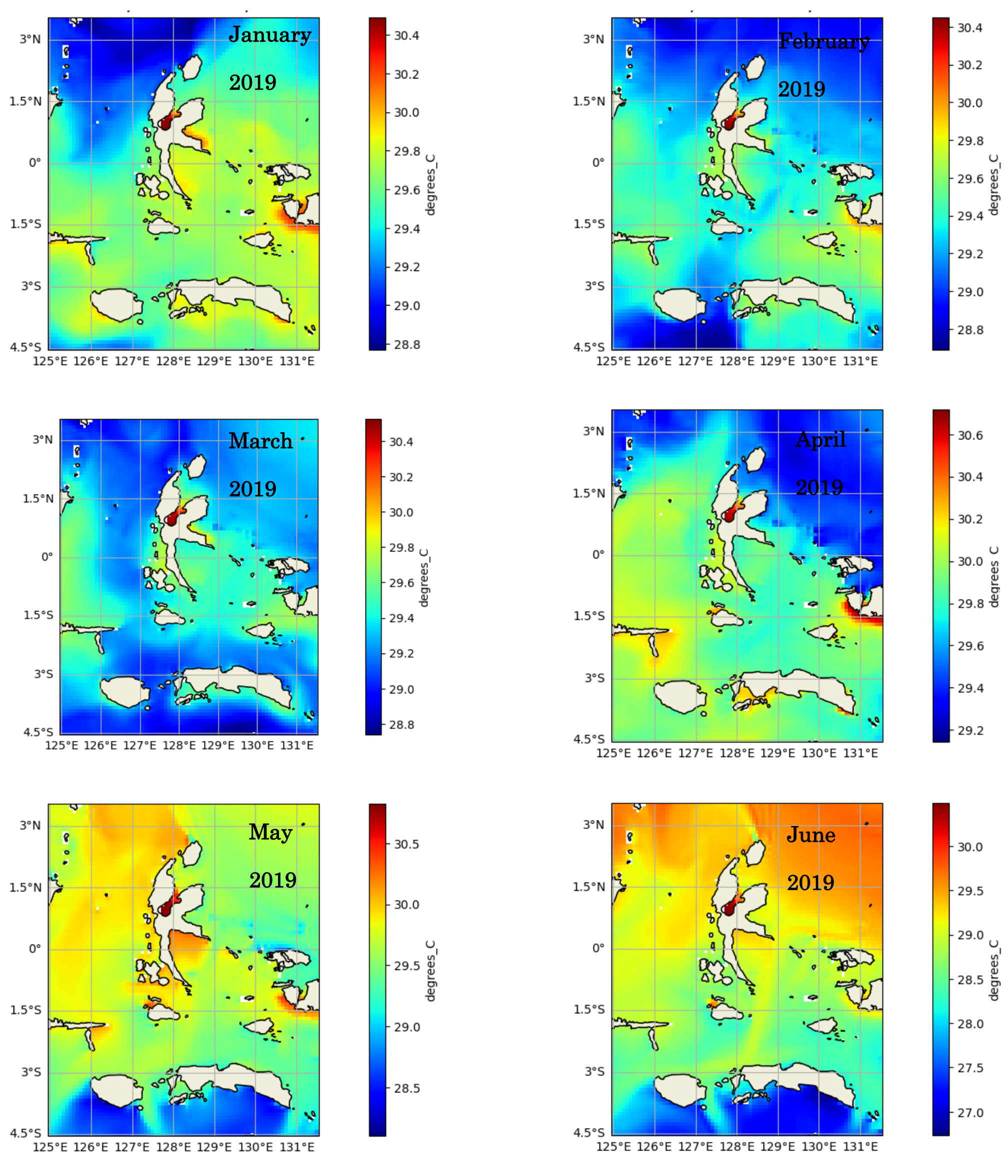


Fig. 2: Variability of sea surface temperature (SST) in Indonesia Seas in 2019.



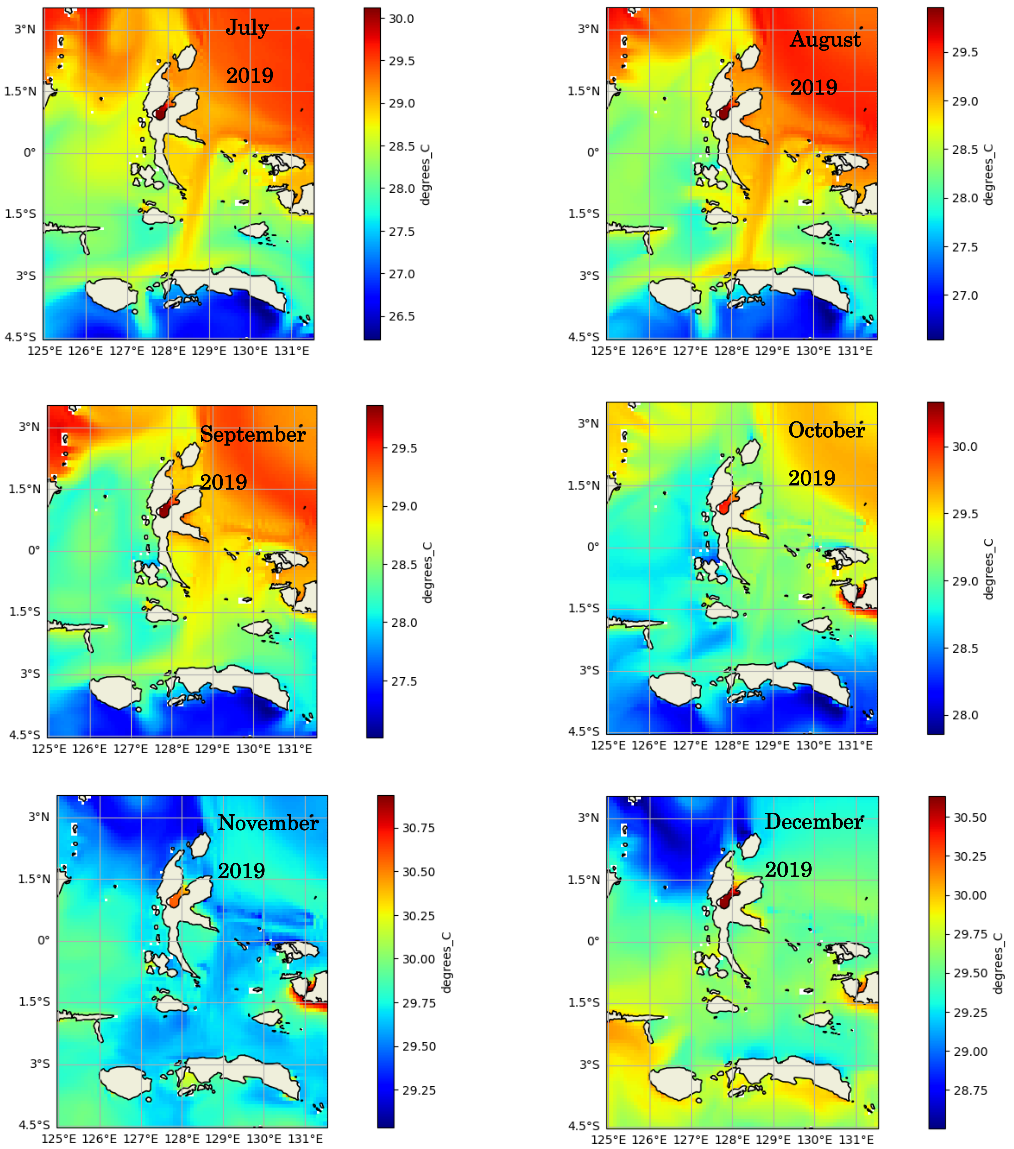


Fig. 3: Variability of sea surface temperature (SST) in Halmahera Seas in 2019.

The distribution of SST variability values in the Halmahera Sea during the January-December 2019 period ranged from 26.25 to 29.05ºC (Fig. 3). Figure 3 presents the spatial distribution of SST values. The distribution of SST values in 2019 experienced the highest SST peak in the eastern season (July, August, and September). The highest SST peak occurs during the East Season (July to September) and lower SST in the West Season (January to April). The lowest decrease in SST variability reached 26.25ºC. The SST value in the 2019 East Season ranged from 25.15 to 29.15ºC. The low SST value compared to other seasons indicates an upwelling phenomenon in the Halmahera Sea.

3.2. Variability of SST in the Indonesian and Halmahera Seas in 2020

The distribution of SST variability values in the Indonesian Sea during the January-December 2020 period ranged from 23.55º-33.50ºC. Figure 4 presents the spatial distribution of SST values. The distribution of SST values in 2020 experienced the highest SST peaks in the East Season (June, July, August, and September) and the West Season (January, February, and March).

The highest SST values during the East Season (June to September) and lower SST in the West Season (January to March) can be associated with the interaction between the ENSO phenomenon and seasonal wind and rainfall patterns[20].

The lowest decrease in SST variability reached 28.70ºC. The SST values in the 2020 East Season ranged from 24.53 to 27.20ºC. The low SST values compared to other seasons indicate an upwelling phenomenon in the Indonesian sea[21].

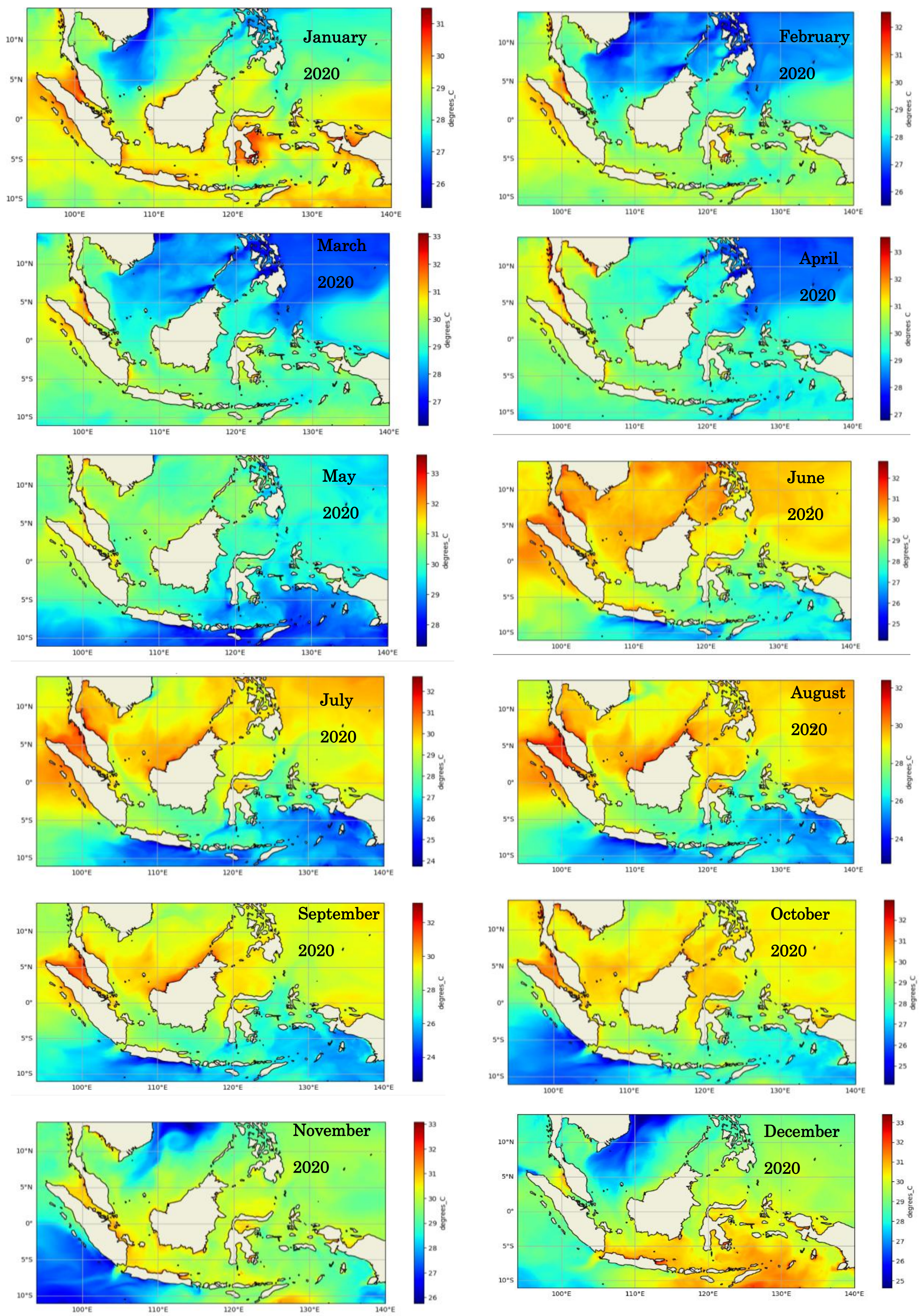
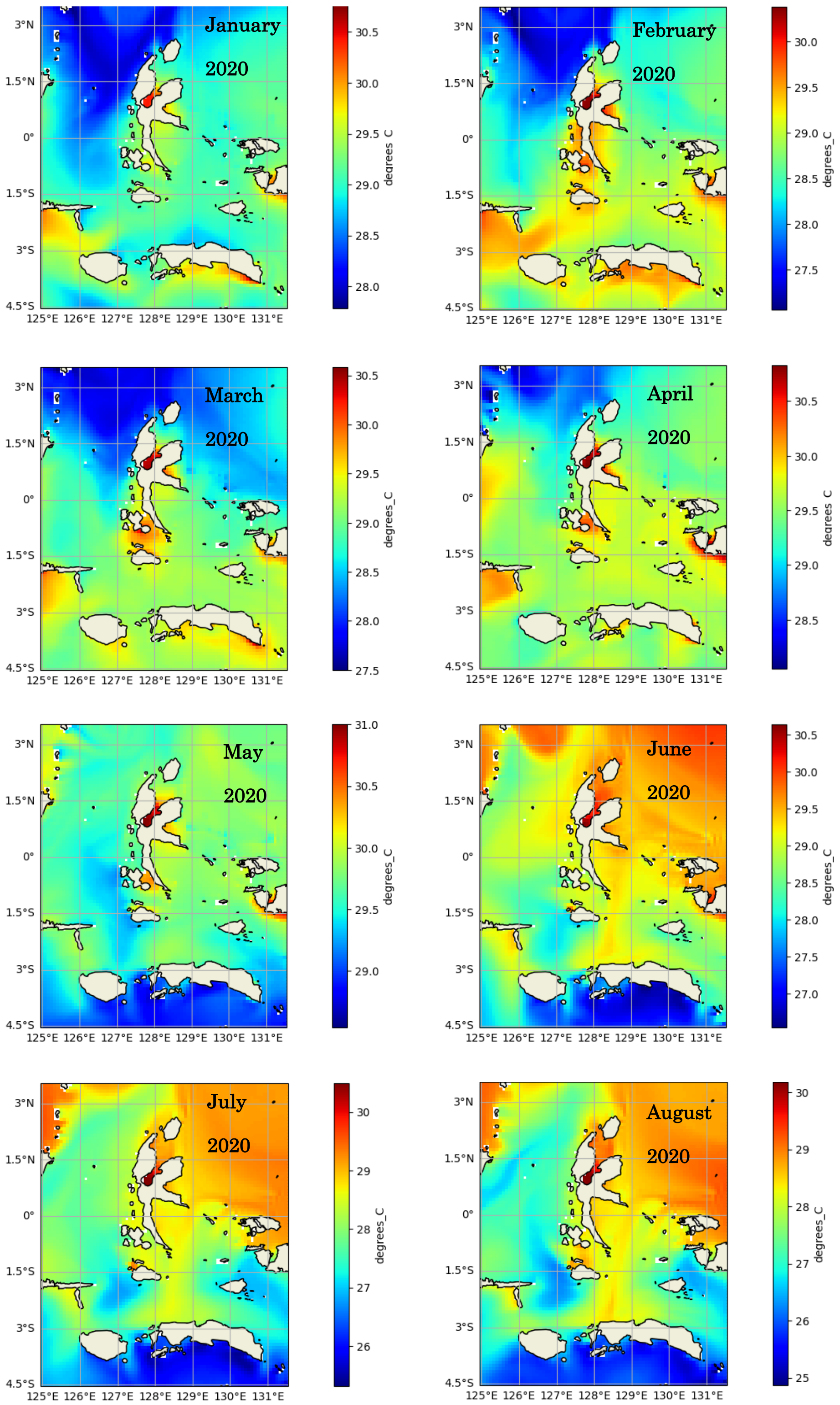


Fig. 4: Variability of sea surface temperature (SST) in Indonesia Seas in 2020.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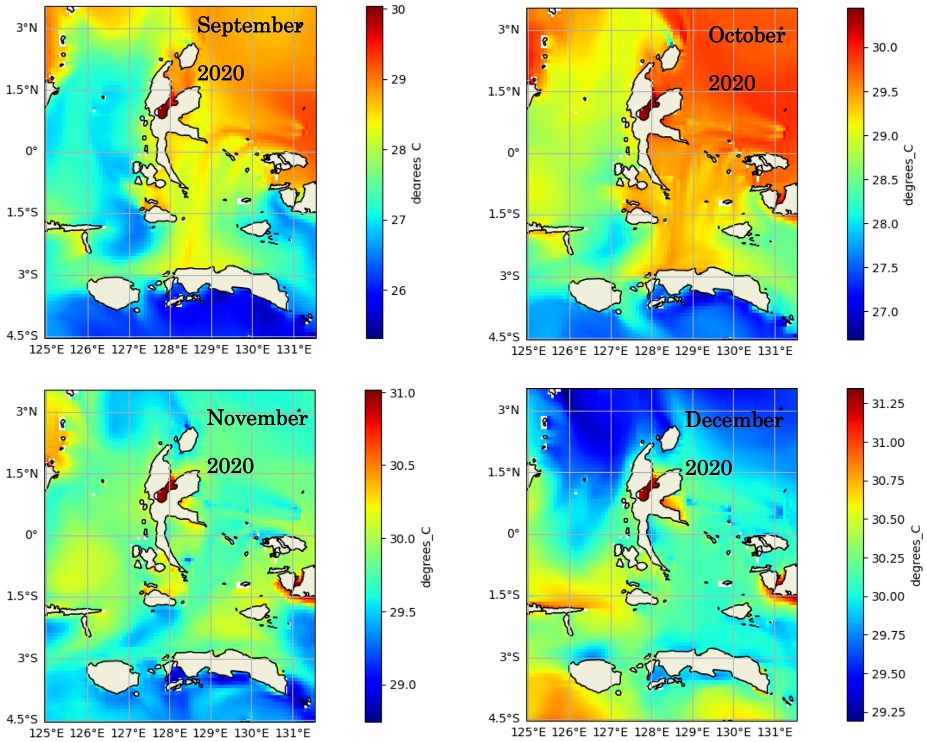


Fig. 5: Variability of sea surface temperature (SST) in Halmahera Seas in 2020.

Understanding SST variability is vital for assessing the ecological health of the Halmahera Sea. The upwelling phenomenon during the East Season not only enhances primary productivity but also affects the distribution and abundance of marine species, including commercially important fish stocks. Furthermore, the SST patterns observed in 2020 suggest potential implications for local climate variability, as changes in ocean temperatures can influence atmospheric conditions and weather patterns across Indonesia.

The distribution of SST variability values in the Halmahera Sea during the January-December 2020 period ranged from 25.25º-31.35ºC (Fig. 5). Figure 5 presents the spatial distribution of SST values. The distribution of SST values in 2020 experienced the highest SST peak in the East Season (July, August, September, October). The highest SST peak occurs during the East Season (July to October) and lower SST in the West Season (January to May). The lowest SST variability decrease reached 25.25ºC. The low SST value in the 2020 East Season ranged from 26.35–29.25ºC. The low SST value compared to other seasons indicates an upwelling phenomenon in the Halmahera Sea.

When La Niña conditions reached their peak in 2020, a comparison of sea surface temperatures (SST) in the Halmahera Sea showed big changes that could affect regional climate patterns and marine biodiversity. This showed the need for more research to figure out what these changes mean for ecosystems and weather systems in the area.

3.3 Variability of SST in the Indonesian and Halmahera Seas in 2021

The distribution of SST variability values in the Indonesian Sea during the January-December 2021 period ranged from 21.95º-33.25ºC. Figure 6 presents the spatial distribution of SST values. The distribution of SST values in 2021 experienced the highest SST peaks in the East Season (August, September, October) and the West Season (December, January, February, and March).

The highest SST values during the East Season (August to October) and lower SST in the West Season in April can be associated with the interaction between the ENSO phenomenon and seasonal wind and rainfall patterns[20]. The lowest decrease in SST variability reached 21.95ºC. The SST values in the 2021 East Season ranged from 29.13 to 27.30ºC. The observed low sea surface temperature (SST) values during this period, in contrast to other seasons, suggest the occurrence of an upwelling phenomenon in the Indonesian Sea. The low SST values compared to other seasons indicate an upwelling phenomenon in the Indonesian sea[22].

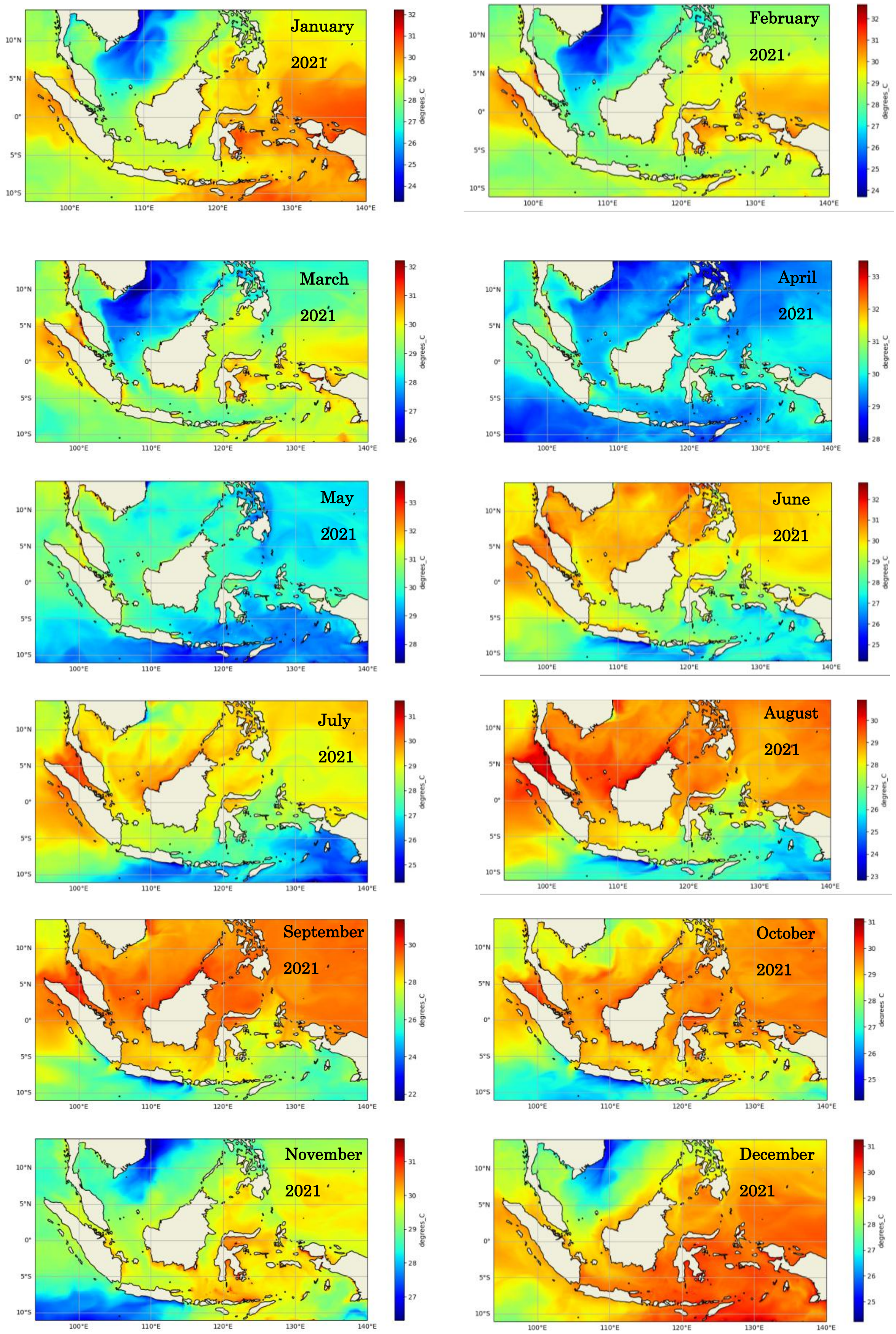
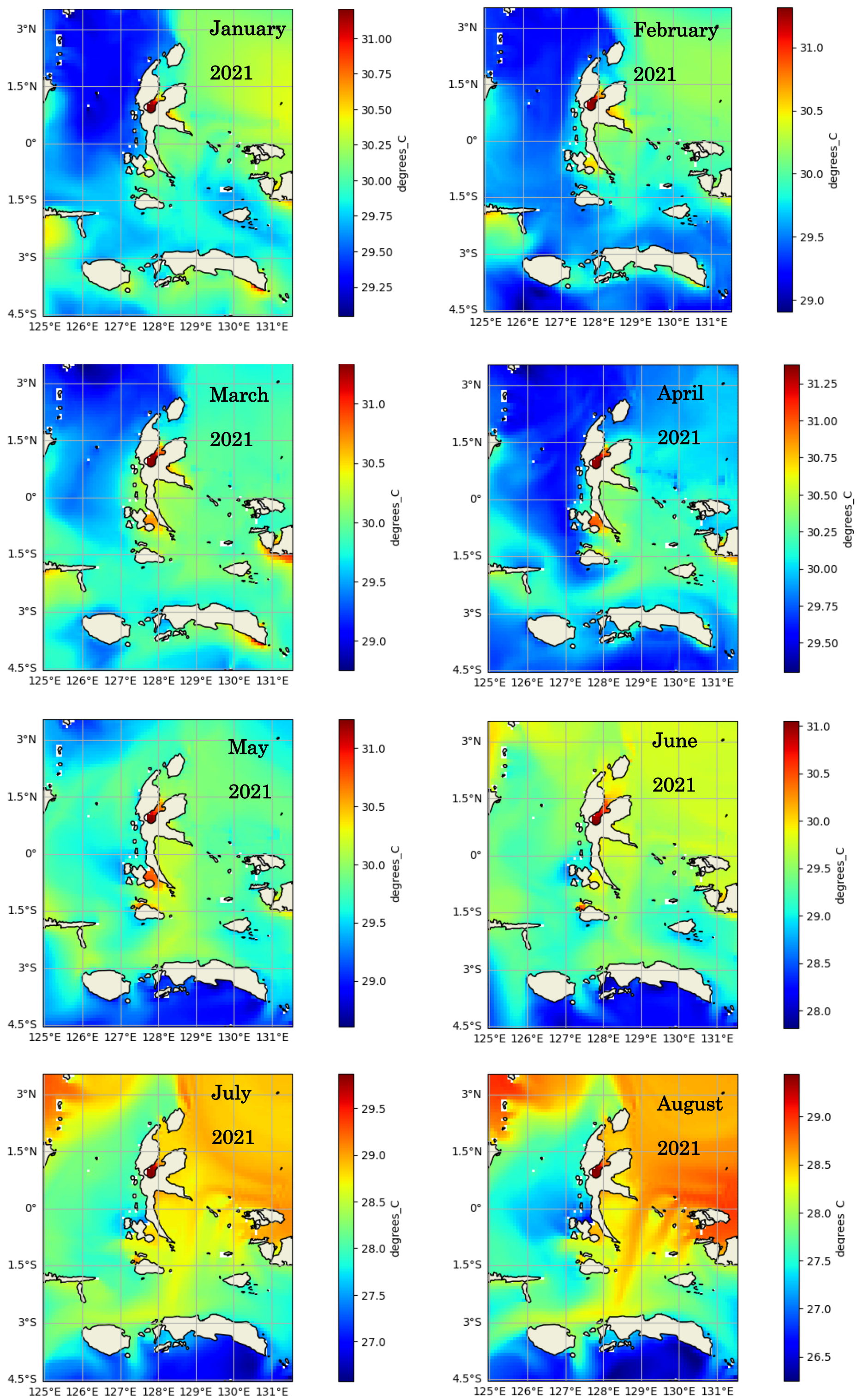


Fig. 6: Variability of sea surface temperature (SST) in Indonesia Seas in 2021.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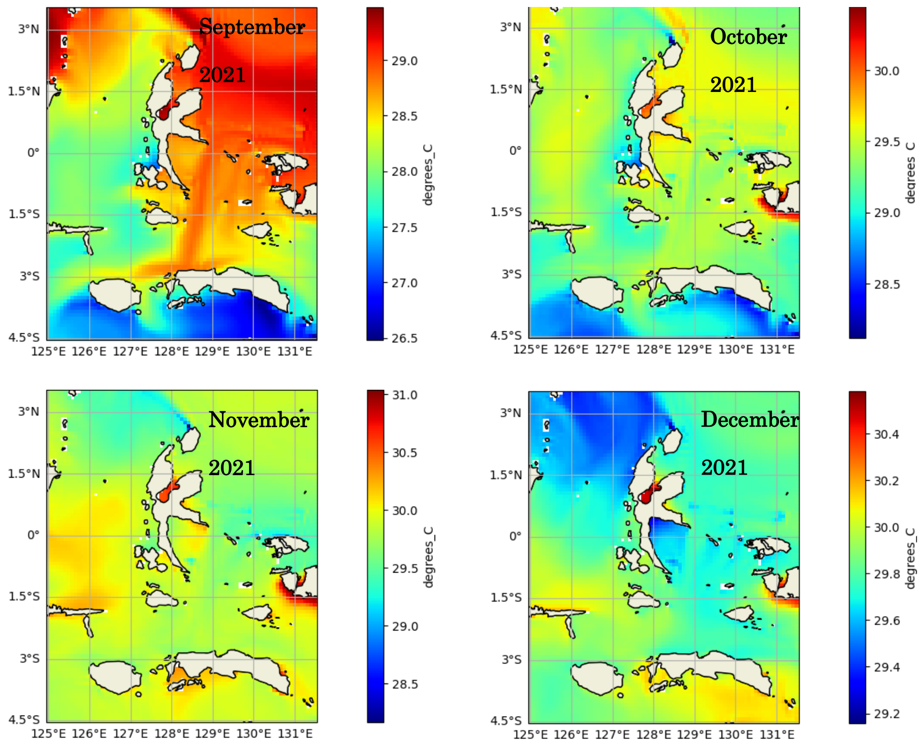

Fig. 7: Variability of sea surface temperature (SST) in Indonesia Seas in 2021.

The distribution of SST variability values in the Halmahera Sea during the January-December 2021 period ranged from 26.05º-31.25ºC (Fig. 7). Figure 7 presents the spatial distribution of SST values. The distribution of SST values in 2021 experienced the highest SST peak in the eastern season (July, August, and September). The highest SST peak occurs during the East Season (July to September) and lower SST in the West Season (January to May). The lowest SST variability decrease reached 26.05ºC. The low SST value in the 2021 East Season ranged from 27.05ºC to 29.08ºC. The low SST value compared to other seasons indicates an upwelling phenomenon in the Halmahera Sea in 2021. In 2021, the SST exhibited its highest peaks during the East Season, particularly in August, September, and October, as well as during the West Season, which includes December, January, February, and March. The elevated SST values observed during the East Season can be attributed to increased solar radiation and favorable climatic conditions, while the peaks in the West Season are influenced by seasonal wind patterns and rainfall variability.

A big part of how these temperature patterns are formed is how the El Niño-Southern Oscillation (ENSO) phenomenon interacts with local weather conditions. This complex interplay affects not only SST but also broader climatic conditions in the region, impacting marine ecosystems and weather patterns. Overall, these observations show the relationship between climate conditions, ocean phenomena, and SST variability that occur in the Halmahera Sea, as well as the impact of La Niña on SST during 2021[23–28]. La Niña conditions, characterized by cooler-than-average sea surface temperatures (SST) in the central and eastern Pacific, significantly influenced global weather patterns and enhanced upwelling in the Indonesian and Halmahera Seas (2019-2021).

3.4. Comparison of SST satellite with CTD observation data

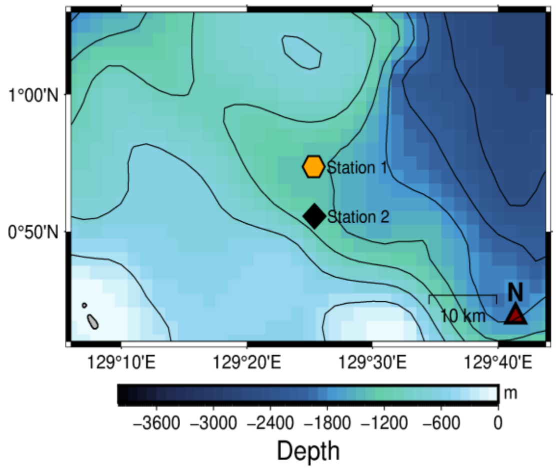

Fig. 8: The location of CTD observation on 3 September 2021 (station 1) and 6 September 2021 (station 2) in the Halmahera Sea.

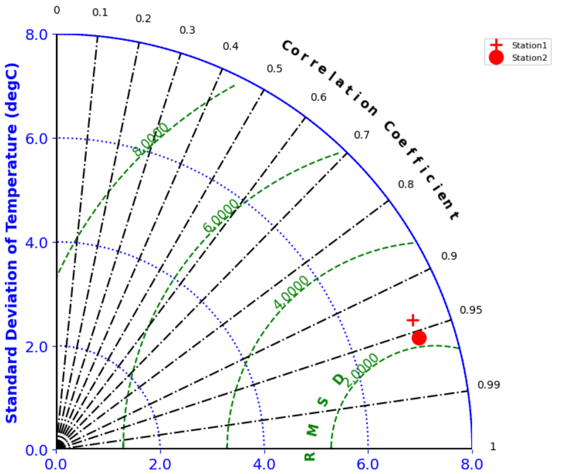

Fig. 9: The Taylor diagram statistical results for stations 1 and 2 of sea surface temperature (SST) data.

Figure 8 shows where our study's CTD data collection took place. Taylor diagram When we compared the SST of CMEMS satellite data to observational CTD data, we got Taylor statistics for Station 1 (Fig. 9). These were coefficient correlation 0.91, RMSD 2.1, and SD 7.0. The Taylor statistics for Station 2 showed a coefficient correlation of 0.93, an RMSD of 2.4, and an SD of 7.3 (Fig. 9).

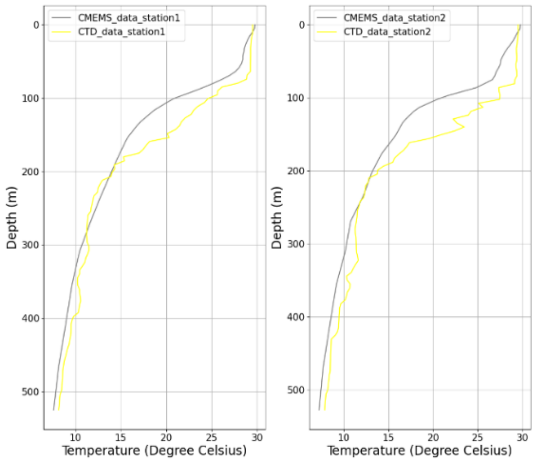

Fig. 10: The vertical distribution of sea surface temperature (SST) based on CMEMS data is shown in grey, while the CTD observation data is shown in yellow in the Halmahera Sea.

Figure 10 shows vertical distribution results that demonstrate a strong correlation between the two sets of data. This demonstrates the ability to compare CMEMS satellite data with SST data. The results of this analysis indicate that CMEMS satellite data has high potential for use in monitoring SST in various locations. The strong correlation between satellite data and CTD observation data confirms that satellite data can provide accurate and reliable information, especially in areas that are difficult to reach by direct measurements. Previous studies have also shown that the use of satellite data in SST studies can improve our understanding of oceanographic dynamics and climate change[29–36]. Therefore, the integration of satellite data in oceanography studies can be an important step to improve the accuracy and efficiency of marine environmental monitoring.

4. Conclusion

The sea surface temperature (SST) variability in the Indonesian and Halmahera Seas from 2019 to 2021 reveals significant seasonal patterns influenced by climatic phenomena such as ENSO events. Both seas exhibited higher SST peaks during the East and lower temperatures in the West, indicating notable upwelling. In 2019, the Indonesian Sea showed more significant SST variability than the Halmahera Sea, while by 2020, the Halmahera Sea experienced a marked reduction in SST. By 2021, the Indonesian Sea saw increased SST variability due to changing climate conditions, whereas the Halmahera Sea maintained its seasonal patterns. The influence of strong La Niña further highlighted the interconnectedness of regional climate dynamics in 2021. Additionally, the strong correlation between satellite data from CMEMS and observational data underscores the reliability of satellite monitoring for understanding SST variations. The highest sea surface temperature (SST) values in Indonesian waters were found in the eastern regions, particularly around the Arafura Sea and the Banda Sea, often exceeding 30ºC during the East Season (June to October).

The analysis revealed that the SST reached its peak during the East Season, specifically in July, August, September, and October. This period is characterized by a significant increase in SST, attributed to various factors such as solar radiation, ocean currents, and atmospheric conditions. Conversely, the wet season (January to May) experienced notably lower SST values, highlighting a seasonal oscillation that influences local marine ecosystems. To mitigate the impacts of climate change in Indonesia, it is essential to establish continuous monitoring systems for sea surface temperatures (SST) using satellite data, which can inform adaptive marine resource management strategies. Engaging coastal communities through education on sustainable practices and resilience-building is crucial, alongside investing in climate-resilient infrastructure to protect vulnerable areas. Additionally, formulating effective policies and fostering international collaborations will enhance efforts to address climate change and promote sustainable development.

Acknowledgements

The author expresses profound gratitude to Batam State Polytechnic, Shanghai Ocean University, and CV. Tizen Construction for providing the necessary instruments for data processing. The Copernicus Marine Environment Monitoring Service aggregates satellite data. We extend our gratitude to the commander and crew of KRI Spica 934 for their execution of the survey during the JALA

CITRA 1 Expedition "AURORA" in 2021. The support of all relevant parties facilitated the preparation of this article to bolster the CTD observation data.

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