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Research article

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EFFECT OF MONSOON PHENOMENON ON SEA SURFACE TEMPERATURES IN INDONESIAN THROUGHFLOW REGION AND SOUTHEAST INDIAN OCEAN

季风现象对印度尼西亚贯流区和印度洋东南部海面温度的影响

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Abstract

Indonesia is influenced by two types of monsoons, namely, the Asian and Australian monsoons. The differences in conditions occurring during these monsoon phenomena can affect sea surface temperatures (SSTs). This study aims to determine the effect of these monsoons on the SSTs in the southeast Indian Ocean and the Indonesian throughflow (ITF) region. SST and geostrophic current data obtained from Copernicus Marine Service and surface wind speed and direction data from the European Center for Medium-Range Weather Forecasts (ECMWF) from March 2019 to February 2020 were statistically and descriptively analyzed. Observational conductivity–temperature–depth (CTD) data obtained in December 2019 were used to identify statistical errors in the Copernicus Marine Service SST data. The results of the SST data verification show a 0.85°C RMSE and 0.6°C MAE; they are significantly correlated at 0.82 with a 95% confidence level. The results of this study generally show that geostrophic currents move to the east, and SST tends to be warmer during the Asian monsoon period than during the Australian monsoon period, which has a cooler SST (with geostrophic currents moving to the northwest). Specifically, the SST conditions in the ITF region and southeast Indian Ocean cool from the MAM period. This cooling period intensifies during the JJA period and subsides in the SON period. The

Australian monsoon, which is dominant during the DJF period, causes warmer-than-average SST conditions in the northern part of Indonesia, particularly the northern part of the ITF.

Keywords: Monsoon, Sea Surface Temperature, Southeast Indian Ocean, Indonesian Throughflow

摘要 印度尼西亚受到两种季风的影响，即亚洲季风和澳大利亚季风。这些季风现象期间发生的条件差异会影响海面温度（SST）。本研究旨在确定这些季风对印度洋东南部和印度尼西亚通流（国际乒联）地区海温的影响。对2019年3月至2020年2月从哥白尼海洋服务中心获得的SST和地转流数据以及来自欧洲中期天气预报中心(ECMWF)的地面风速和风向数据进行了统计和描述性分析。2019年 12 月获得的观测电导率-温度-
深度(CTD)数据用于识别哥白尼海洋服务SST数据中的统计误差。SST数据验证结果显示0.85° C均方根误差和0.6° C硕士；它们在0.82处显着相关，置信度为95%。本研究的结果普遍表明，地转流向东移动，亚洲季风期的海温比澳大利亚季风期的海温偏暖，而澳大利亚季风期的海温较低（地转流向西北移动）。具体而言，国际乒联地区和印度洋东南部的SST条件从MAM时期开始变冷。这种冷却期在JJA期加强，在儿子期消退。在DJF期间占主导地位的澳大利亚季风导致印度尼西亚北部，特别是国际乒联北部的 SST 条件高于平均水平。

关键词: 季风、海面温度、东南印度洋、印度尼西亚穿流

I. INTRODUCTION

Indonesia is influenced by two types of monsoons, namely, the Asian and Australian monsoons [1], [2]. Monsoon winds alternately move across Indonesia throughout the year within six-month periods, namely, April to September (east monsoon winds) and October to March (west monsoon winds) [3]. The naturally cold Asian monsoon winds blow from the Eurasian continent to warm sea surface areas in the eastern and southeastern parts of Asia during winter in the Northern Hemisphere (NH) [4]. Australian monsoon winds move from the mainland of the Australian continent toward Asia during winter in the Southern Hemisphere (SH). These two systems of monsoon winds can affect the oceanographic parameters of waters, such as winds, currents, and distributions of sea surface temperatures (SSTs).

Wind movements can affect the direction of geostrophic currents at sea surfaces [5]. The water masses in the water surface layer can mix due to the existence of strong wind movements on the water surface. Accordingly, the temperature distribution becomes uniform. Winds in the southern waters of Java blow from the Australian continent toward the west [6]. This causes surface water masses to move from the south of Java Island to the west of the Indonesian Ocean. This movement leads to circulation of water masses from the inside (which is low in temperature) upward to replace the displaced surface water masses.

The circulation of periodic monsoon winds in the Java Sea region causes variations in the SST; during the Australian monsoon period, the winds and currents in the Java Sea move from east to west, bringing a relatively cooler water mass [7]. During the Asian monsoon period, the water masses from the South China Sea fill the Java Sea and move eastward following the direction of wind and current movements. In agreement with previous studies, Manjunatha et al. stated that the SSTs in the Indonesian throughflow (ITF) region are lower during the summer (May–August); low values are identified in the eastern region of Indonesia, and they further decrease toward the west due to the Australian monsoon activity [8]. In addition, a cooling temperature is seen in early May, considerably decreases in July, and starts to normalize in late August.

This study aimed to (1) determine the effect of monsoon phenomena on the SSTs in the ITF region and the southeast Indian Ocean and (2) examine the distribution of SSTs at the research locations due to changes in wind direction and ocean currents related to the circulation of monsoon winds.

II. Materials and Methods

A. Research Location

This study focuses on the southeast Indian Ocean and the ITF region (E 98°–120°, N 5°–S 15°). This location coincides with the position of an in situ SST data collection (conductivity–temperature–depth [CTD]) during a sailing voyage. Figure 1 shows a map of the study area.

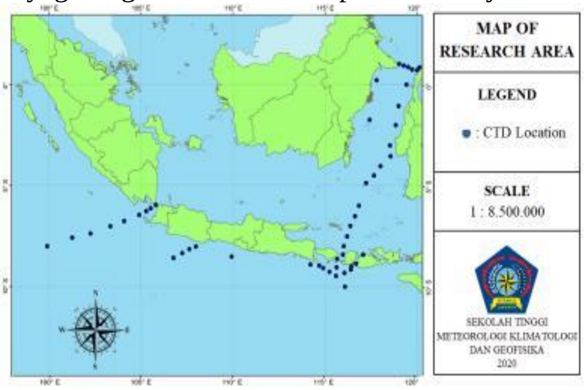

Figure 1. Map of the research area

B. Data

Several types of data were used in this study. SST data and geostrophic current models with a 0.083° × 0.083° spatial resolution and 1 h temporal resolution were obtained from Copernicus Marine Service. For the SST parameters, hourly model data were obtained from November 19, 2019, 00:00 (UTC), to December 18, 2019, 00:00 (UTC), according to the time of in situ data collection in the sailing voyage. These model data were in the form of monthly averages from March 2019 to February 2020; this format was also applied to the SST parameters and geostrophic current models, which were used to observe the seasonal conditions of these parameters.

The other parameters used in this study were surface wind direction and speed. These parameter data were in the form of reanalysis data obtained from the European Center for Medium-Range Weather Forecasts (ECMWF); they had a 6 h temporal resolution and 0.125° × 0.125° spatial resolution and were acquired from March 2019 to February 2020. Data on the direction and speed of surface winds were used to observe the seasonal conditions.

SST model data were assessed with CTD observational data. The CTD data were spread over 49 points covering the southern waters of the Java Sea or the southeast Indian Ocean and the delineated ITF area in Figure 1.

C. Method

This research was conducted using statistical and descriptive methods. The statistical method was carried out during the assessment process of the Marine Copernicus SST model with in-situ observation data from 49 CTD points. The assessment was conducted by finding the values of RMSE, MAE, regression value (r-value), correlation coefficient, and probability value (p-value). Meanwhile, the descriptive method was used to examine all the parameters used in this study. The parameters analyzed in this study include the conditions of surface wind, geostrophic current, and sea surface temperature.

A simple statistical method was used to determine how much deviation occurs amongst the SST model data compared to the results obtained from observations, which is significantly necessary to evaluate the model performance [9], [10]. SST model verification was conducted by performing Root Mean Square Error (RMSE), Mean Absolute Error (MAE), finding the correlation and regression coefficient values and the probability value. In geoscience, there have been many studies presenting RMSE as a standard matrix for representing model errors [11], [12]. The combination of RMSE and MAE test methods (not limited to only these two methods) is often used to assess the performance of a model [13].

RMSE (Root Mean Square Error) is the root mean square obtained from the difference between the model output and the actual data or observation results. The RMSE formula is illustrated as follows [9]:

$$RMSE = \sqrt{\frac{\sum (X_i - Y_i)^2}{n}} \quad (1)$$

MAE is the result of the absolute value obtained from the difference between the value of the model output and the actual data or observation results. The following formula is used to calculate the MAE [9]:

$$MAE = \frac{\sum |X_i - Y_i|}{n} \quad (2)$$

According to Levin et al. [14], regression value is used as a reference to determine the strength of correlation among variables and their properties. This regression value is the square of the correlation coefficient value. The availability of past observation data from a variable can be used to predict this variable by using regression values. In the calculation, the Pearson correlation coefficient value can be obtained using the following formula [9]:

$$r = \frac{n\sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{\{n\sum X_i^2 - (\sum X_i)^2\}\{n\sum Y_i^2 - (\sum Y_i)^2\}}} \quad (3)$$

where X_i is the calculated value, Y_i is the original or true value, and n is the total number of the data.

A probability value is necessary to find the significance of the correlation between two variables. The probability value (p-value) is used to measure the amount of evidence that contradicts H_0, meaning that H_0 will be more likely rejected if the probability value is smaller. 0.05 is the maximum probability value used in this study which means that the correlation has a 95% confidence level.

III. Results and Discussion

A. Verification of SST Data

The data of the SST model were obtained from Marine Copernicus, previously verified with observational data taken from 49 CTD points. The results of the statistical test can be seen in Table 1.

Table 1.
Result of SST model verification obtained by the statistical test

Parameter of Statistical Test	Value
RMSE	0.846773865℃
MAE	0.6018℃
Regression (r^2)	0.676794057
Correlation Coefficient (r)	0.82267494
Probability Value	4.1398×10^{-13}

As seen in Table 1, the values of RMSE and MAE are quite small. This indicates that the model's error is quite small, and the model can represent the real SST condition. The correlation coefficient (r) between SST model data and CTD data has a unidirectional relationship since the correlation coefficient is positive. In addition, the probability value (p-value) in Table 1 looks very small as the p-value is less than 0.05. Accordingly, the correlation is statistically significant and has more than a 95% confidence level.

B. Analysis of Surface Wind Conditions

Surface wind conditions became one of the most important parameters for this research. It is linked to the role of surface winds in the movement of geostrophic currents and the mixing of topsoil water. In addition, the surface winds which move geostrophic currents also play a role in the distribution of sea surface temperatures. Figure 2 shows the seasonal surface wind conditions from March 2019 to February 2020.

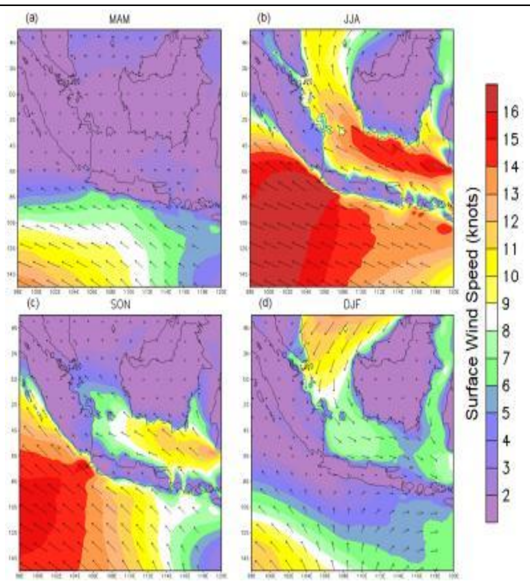

Figure 2. Distribution of winds' direction and average speed in (a) MAM, (b) JJA, (c) SON, and (d) DJF season in 2019–2020

In transitional season I (MAM), the wind direction in Indonesian waters was dominated by the southeast, with the average wind speed in the Southeast Indian Ocean ranging from 3–8 knots, while the wind speed in Makassar Strait was classified as low, 2–4 knots (Figure 2a). In the first transitional season, there was a transition between Asian or western monsoons and Australian or eastern monsoons. This made the wind direction tend to be irregular. The speed was not significant, which caused the distribution of sea surface temperature in the Southeast Indian Ocean and Makassar Strait to increase.

During the eastern season (JJA), there was an increase in wind speed in the Indonesian waters area (Figure 2b). The wind blew from the southeast to the northwest at 11–16 knots speed in the Southeast Indian Ocean. Meanwhile, in the Makassar Strait area, the wind moved to the northwest and the north ranging from 6 – 14 knots. In the eastern monsoon, the Australian or eastern monsoon strengthened, which was indicated by the increase in the speed of the eastern winds in most Indonesian waters. This has caused the sea surface currents to move strongly to the northwest, allowing sea surface temperature distribution in the Southeast Indian Ocean and Makassar Strait to decrease.

In the second transitional season (SON), the wind direction in the Southeast Indian Ocean still moved relatively from the southeast to the northwest, but with lower speeds ranging from 10–15 knots (Figure 2c). Furthermore, the wind direction in the Makassar Strait moved to the northwest and the north at 3–9 knots speed. In the second transitional season, there was a transition between the Australian or eastern monsoon and the Asian or western monsoon. This caused the wind direction likely to be irregular. The speed tended to decrease, which made the distribution of sea surface temperature in the Southeast Indian Ocean and Makassar Strait more than during the JJA season.

During the west monsoon (DJF), the wind direction in the Indonesian waters reversed towards the southeast (Figure 2d). Moreover, in the Southeast Indian Ocean region, wind directions were moving from the northwest and the southeast with 2–8 knots speed. Meanwhile, the wind shifted to the south and the southeast with 4–9 knots speed in Makassar Strait. In addition, the Asian monsoon or the west monsoon strengthened in the western region, which was indicated by an increase in the western wind speed. Accordingly, this allowed an increase in sea surface temperature in the Southeast Indian Ocean and Makassar Strait due to the existing surface currents that carried heat to the southeast and the south.

C. Analysis of Geostrophic Current Condition

Ocean current can be defined as the movement of water mass from one place to another. In fundamental, ocean current is generated by solar heating, where ocean currents play a role in transferring heat from one place to another as a mechanism to balance the energy on earth. Besides, the circulation of ocean currents (surface) is also influenced by the wind, of which the currents that occur correspond to the wind patterns blowing. Figure 3 shows the surface current conditions for each season (DJF, MMA, JJA, and SON). Therefore, it is evident that the current pattern is correlated to the wind pattern that blows.

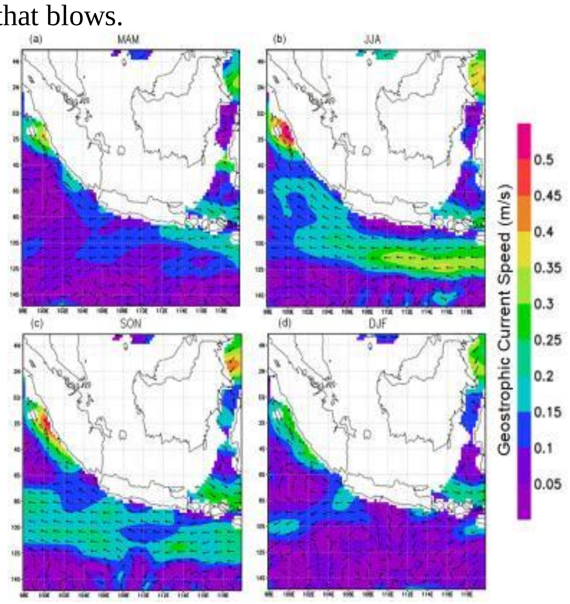

Figure 3. Average geostrophic current conditions in each in (a) MAM, (b) JJA, (c) SON, and (d) DJF season in 2019–2020

In the MAM season, it can be seen that in the waters of the Southeast Indian Ocean, the current moved from the east to the west at 0.1–0.3 m/s speed (Figure 3a). Meanwhile, the current in the Makassar Strait area moved from the south to the north. Such conditions indicated heat transfer from the east to the west for the Southeast Indian Ocean waters and from south to the north in the Makassar Strait area.

In addition, it can be seen that in the JJA season, the currents of the waters of the Southeast Indian Ocean moved from the east to the west intensively with 0.15–0.45 m/s speed (Figure 3b). Besides, the current in the Makassar Strait area moved from the south to the north at 0.05–0.2 m/s speed. These current conditions indicated heat transfer from east to west for the waters of the Southeast Indian Ocean and heat transfer from south to north in the Makassar Strait area.

In the SON season, it could still be seen that the currents of the waters of the Southeast Indian Ocean moved from the east to the west, but at a slower speed, i.e., 0.15–0.3 m/s (Figure 3c). Meanwhile, in the Makassar Strait area, there was a current from the Sulawesi Sea towards Makassar Strait at 0.25–0.45 m/s speed. The current conditions indicated heat transfer from east to west for the waters of the Southeast Indian Ocean and heat transfer from the Sulawesi Sea to the south in the Makassar Strait area.

The current waters of the Southeast Indian Ocean during DJF season moved from the east to the west, but at a slower speed, i.e., 0.15–0.3 m/s (Figure 3d). Furthermore, there were currents in the Makassar Strait area originating from the Sulawesi Sea towards the Makassar Strait with 0.2–0.3 m/s speed. Those current conditions showed heat transfer from east to west for the waters of the Southeast Indian Ocean and heat transfer from the Sulawesi Sea to the south in the Makassar Strait area.

D. Analysis of Sea Surface Temperature Condition

In this study, the SST model data obtained from Marine Copernicus showed fairly small error result. Thus, this SST model could be used for further analysis concerning SST conditions. Figure 4 shows the seasonal condition of SST from March 2019 to February 2020.

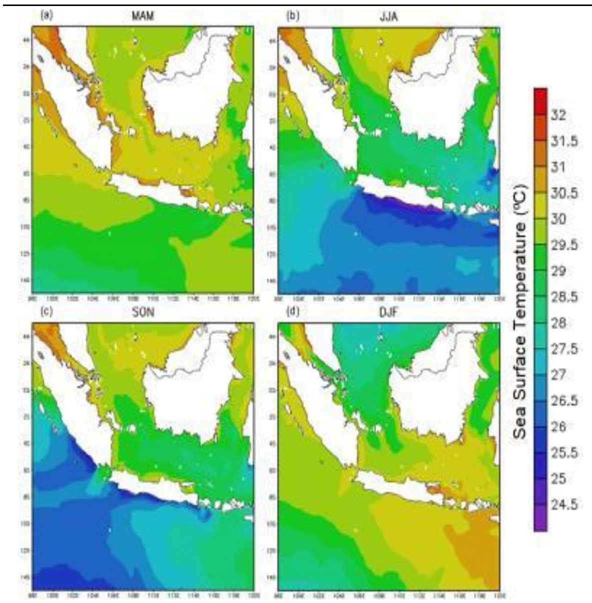

Figure 4. Average sea surface temperature conditions in each in (a) MAM, (b) JJA, (c) SON, and (d) DJF season in 2019–2020

Sea surface temperature conditions are related to surface wind condition and wind-driven ocean current. During the period March – April – May (MAM), which was a transitional period, ITF region and the Southeast Indian Ocean in particular showed the same SST conditions, ranging from 29–30°C (Figure 4a). This might be associated with the surface wind conditions for the MAM period, as shown in Figure 2a, which have been seen blowing from Australia.

The peak of The Australian Monsoon in the JJA period brought cold air masses from the Australian mainland which was experiencing winter. The wind carried cold air masses and interacted with the ocean. Consequently, the currents from the south which were cold mixed and spread over the southern waters of Indonesia. As seen in Figure 4b, SST conditions in the Southeast Indian Ocean became cooler than in the previous period, from approximately 27°C to less than 24°C in the south of East Java.

The SON period marked the end of the cooling phase of SST in the Southeast Indian Ocean and ITF (Figure 4c). If the areas with the lowest sea surface temperatures in JJA period were centered in the south of Central Java and East Java, during SON period such regions shifted to the south, i.e., West Java-Banten and southwest of Lampung. This corresponded to the wind and geostrophic currents which were also stronger around these areas (Figure 2c and Figure 3c). Meanwhile, the SST conditions in the ITF area during the SON period tended to be exactly the same as the conditions of the JJA period.

At the beginning of the DJF period, the Asian cold monsoon became active, causing the Karimata Strait area to be colder than other areas. On the other hand, with the arrival of summer in the southern hemisphere, sea surface temperature conditions in the Southeast Indian Ocean and southern ITF also got warmer ranging from 30–31ºC (Figure 4d). In contrast, in the northern part of ITF, the SST conditions decreased due to the influx of cold currents from the Pacific Northwest Ocean.

E. Analysis of Sea Surface Temperature Condition during Monsoon Anomaly

At the time of sailing to collect CTD data, there were quite different patterns compared to the average DJF period. Figure 5 shows the average sea surface temperature conditions from November 19, 2019, to December 18, 2019.

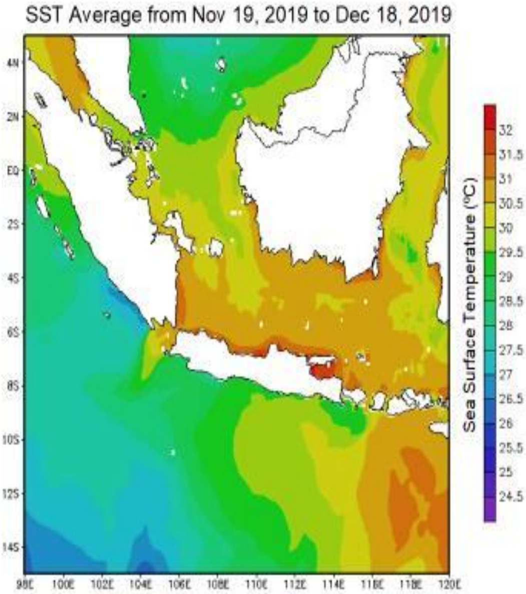

Figure 5. Average sea surface temperature conditions from November 19, 2019, to December 18, 2019

As the sun position was in the Southern Hemisphere, the territorial waters of northwest Australia, the Java Sea, and ITF had higher SST than the average SST during the DJF period. However, the southern areas of Banten - Central Java and the southwest of Sumatra Island had lower SST than the average SST during the DGF period. Based on the SST conditions in the northern part of ITF and in the Karimata Strait, which were still warmer than in the seasonal average conditions, it can be concluded that the Australian monsoon is more dominant than the Asian monsoon. The DJF period normally was dominated by the Asian monsoon. In December 2019 conditions, the Australian monsoon was still more dominant. This can be seen in the 850 mb wind conditions during the second ten-day period (the local term for ten days' duration is *dasarian*) of December 2019 (Figure 6a). The flow of air masses in the southern part of

Indonesia was dominated by eastern winds, i.e., air masses originating from the Australian continent. Due to this wind flow from Australia, there was a distribution of hot air masses to the southern region of the Indonesian maritime continent.

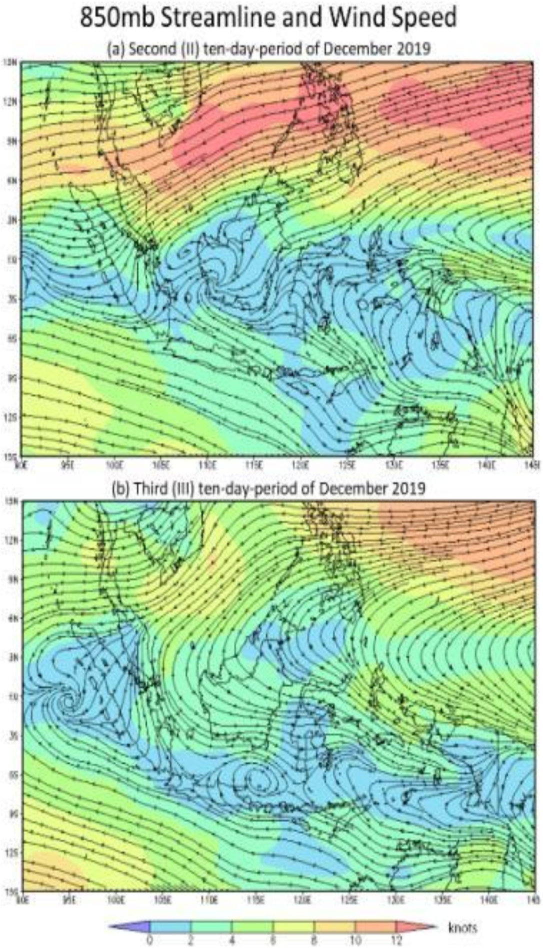

Figure 6. Wind condition of 850 mb layer in (a) the (II) second and (b) third (III) ten-day-period in December 2019 [15], [16]

Entering the third ten-day period of December 2019, air masses flowing into the territory of Indonesia were largely dominated by western winds, i.e., air masses coming from the Asian continent (Figure 6b). This indicates that the Asian monsoon dominated in most areas of Indonesia.

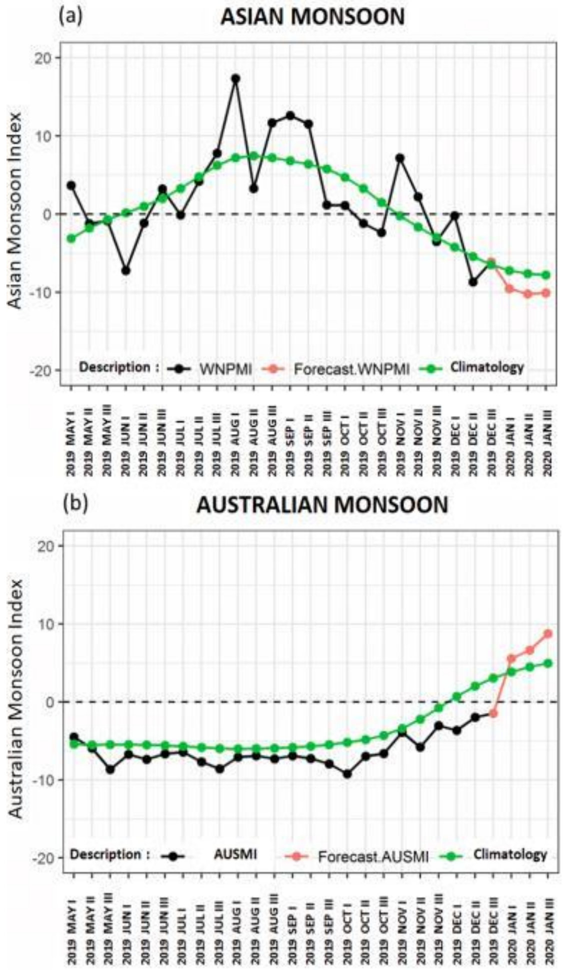

Figure 7. Graph of (a) Asian and (b) Australian monsoon indexes until the third ten-day-period of December 2019 [16]

Based on the Asian monsoon index or the Western North Pacific monsoon index (WNPMI), the Asian monsoon was active in the second ten-day period of December 2019, and its climatology can be seen in the graph (Figure 7a). However, at the same time the presence of the Australian monsoon was more influential for most parts of Indonesia (Figure 7b). This can be seen in the Australian monsoon index (AUSMI), which was stronger than its climatological value or stronger than its normal value. In consequence, it was able to flow warm air masses from the Australian continent to Indonesia.

The Asian monsoon was considerably more dominant in the third ten-day period of December 2019 than the Australian monsoon, as seen in the Asian monsoon index, which was stronger than its climatological values (Figure 7a). In contrast, the Australian monsoon was starting to weaken and was even predicted to be inactive at the first ten-day period of January 2020 (Figure 7b).

The conditions of the monsoon wind play a big role in the distribution of sea surface temperatures. Due to the dominance of the

Australian monsoon until the second ten-day period of December 2019, the condition of SST around Indonesia was also affected. This effect can be seen through the CTD data and the SST model data in Figure 5, which explains that SST conditions for the sailing period of November 19, 2019, to December 18, 2019, tended to be warmer than the average conditions of the DJF period.

IV. Conclusion

Based on the results above, it can be concluded that the verification results on the sea surface temperature model from Marine Copernicus showed a small error, i.e., with 0.85°C RMSE value, 0.6°C MAE, and also 0.82 correlation value with the confidence level higher than 95%. Thus, the SST model data is good enough to represent the SST conditions in this study.

The scientific novelty of the article also consists of a conducted large-scale study describing the influence of the monsoon phenomenon on SST conditions and explaining the monsoon anomaly that has an impact on SST conditions, especially in the research area. Sea surface temperature conditions in the ITF region and the Southeast Indian Ocean have experienced cooling since the MAM period. The cooling peak was in the JJA period and started to moderate in the SON period.

The Australian monsoon, which was more dominant during the DJF period, is a monsoon anomaly because usually, during the DJF period, it has entered the Asian monsoon in IMC. Thus, this condition resulted in warmer SST conditions than the average condition for the northern part of Indonesia, specifically in the northern part of ITF.

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