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Impact of SST Anomalies on Coral Reefs Damage Based on Copula Analysis

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ABSTRACT

The condition of coral reefs in Indonesia is alarming. One of the influenting factors of coral reefs damage is extreme climate change. The aim of this study is to determine the relationship of climate change, that is Sea Surface Temperature (SST) anomaly index, and coral reefs damage in West, Central and East Region of Indonesia. The method used in this study is Copula analysis. Copula is one of the statistical methods used to determine the relationship of two or more variables, in which case the distribution can be normal or not. First, data is transformed into Uniform [0,1] domain. Then, Copula parameter is estimated to get significance parameter. Lastly, the best Copula that has the highest log likelihood value is selected to represent the relationship of data. The result indicates that percentage of coral reefs damage in West and Central Region has relationship with SST Nino 4, while coral reefs damage in East Region does not have relationship with any of SST Nino anomalies. In West Region, the best Copula represents the relationship is Gaussian Copula (parameter = -0.32); it concludes that the higher the value of SST Nino 4, the lower the percentage of coral reefs damage and otherwise. While in Central Indonesia, Frank Copula (parameter = -4.89) is selected; it does not have tail dependency so that the SST Nino 4 and the percentage of coral reefs in damage condition in Central Region has low correlation.

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A. INTRODUCTION

According to data of the Oceanographic Research Center Indonesian Institute of Sciences in 2017, as much as 35.15% of coral reefs in Indonesia are in bad/damaged status (live coral cover 0-25%), 35.06% are in sufficient status (live coral cover 26-50%), 23.40% are in good status (live coral cover is 51-75%), the remaining 6.39% are in very good status (live coral cover 76-100%). That indicates that Indonesias coral reefs ecosystem are in critical condition. Bismo (2013) stated that the climate change can cause the coral reefs bleaching phenomenon with varying degree of severity. El-Nino which is a climate disturbance with the characteristics of increasing Sea Surface Temperature (SST) above the hottest average temperature in a relatively long period of time is one of the causes of coral reef damage. Variability in SST has high correlation to the movement of currents that are generated by winds blowing over the sea surface (Mashita and Lumban-Gaol, 2019). The top value of SST anomaly that influences the risk of the coral bleaching was found in 2010. Bleaching and coral damage were found at locations with high SST anomaly, nitrate that has low value, and phosphate (Ampou et al., 2020).

The previous studies on climate change and coral reefs ecosystem that have been carried out included the following: Puspasari et al. (2015) studied the interaction between Southern Oscillation Index (SOI) and ecosystem of ecosystem and the condition of coral fish. The analysis used is descriptive analysis to the temporal data, principal component analysis and t-test for catch per unit effort (CPUE) of reef fishes. The results show that SOI has effect on coral reef ecosystem and reef fishes CPUE; Speers et al. (2016)

examined the effect of climate change and ocean oxidization on coral reefs on an segmented ecological economic model, resulting that if there is damage on coral reefs, losses are estimated to include seize the production of fisheries, resulting in reduced prosperity; Then Susiloningtyas et al. (2018) studied the relationship of the destruction level of coral reefs and climate change index in Nusa Dua and Nusa Penida, Bali Province, Indonesia based on secondary data of the analysed LANDSAT 7+ and LANDSAT 8 OLI. The analysis performed is descriptive and quantitative analysis. The result indicates that there is the difference about level of coral reefs destruction in 2012 and 2016.

Several previous studies that have been carried out have shown that coral reef ecosystems can be disturbed due to extreme climate change. Those studies have not considered the statistical aspects that show the relationship of the damaged condition of coral reef habitats and climate change. It is interesting for researchers to analyze the relationship between conditions of damage to coral reef habitats and climate change using statistical methods in extreme case as the novelty of this research.

In this study, the researchers determined the relationship between the coral reefs damage condition and climate change in the three Indonesian coral reefs regions, those are the West, Central and Eastern Indonesia (according to COREMAP - The Indonesian Institute of Sciences). The data of coral reefs damage condition used is the percentage data of coral reefs in each study area that has bad/damaged status (live coral cover 0-25%), while climate change data used is Sea Surface Temperature (SST) anomalies, including: SST Nino 1 + 2, Nino 3, Nino 3.4, and Nino 4 anomaly (according to NOAA National Weather Service Climate Prediction Center). All those data are collected from 1999 until 2017. The researchers used Copula to analyze this case.

In statistics, a dependency of multivariate variable can be seen by using Copula technique (Hidayat, 2019). Copula is one of the statistical methods used to determine the relationship of two or more variables, in which case the distribution can be normal or not. To describe the relationship between two variables, correlation or regression can be used; but Copula is excellent to use in the case of extreme events because it can clearly describe dependencies at extreme points. This diversity of copula functions with specific dependence structures makes it impossible to compare different functional forms for copulas (Bhatti and Do, 2019). The aim of this study is to indicate the relationship of coral reefs damage condition and SST Nino by using Copula method, then it results the Copula parameter that represents the relationship of the data.

If there is a random vector $\boldsymbol{X}$ with m-dimensions which has marginal distribution function $\boldsymbol{F} = F_{X_1}, F_{X_2}, \ldots, F_{X_m}$ in non-decreasing domain, R, that are $F_{X_1}(-\infty) = 0$ and $F_{X_1}(\infty) = 1$, then according to Sklar's Theorem in Umeorah et al. (2019), the joint distribution is:

$$F_X(x) = C_X\left(F_{X_1}, F_{X_2}, \ldots, F_{X_m}\right) \tag{1}$$

where $C_X[0,1] \times \ldots \times [0,1] \to [0,1]$ is joint distribution of transformation random variable $U_j = F_{X_j}(x_j)$ for $j = 1, 2, \ldots, m$, with U_j has marginal ditribution of Uniform.

If the marginal distribution functions $F_{X_1}, F_{X_2}, \ldots, F_{X_m}$ is continuous then Copula function C_X is unique (Umeorah et al., 2019), instead of specifying a multivariate distribution F, the structure of dependency could be modelled by identifying the marginal function $F_{X_j}(x_j)$ and a copula C_X. Copula function C_X could be written as:

$$C_X\left(u_1, u_2, \ldots, u_m\right) = \int_0^{u_1} \ldots \int_0^{u_m} C_X\left(u_1, u_2, \ldots, u_m\right)\ du_1 \cdots du_m \tag{2}$$

where C_X is density equation of Copula. Copula is joint distribution function or multivariate distribution function for a uniform marginal distribution. There are two categories of Copula Families, namely Elliptical Copula and Archimedean Copula (Nafii et al., 2023).

1. Elliptical Copula

Elliptical Copula is a Copula of elliptical distributions, consisting of Gaussian Copula and Student's t-Copula. Elliptical distributions are frequently used in robust statistics to appraise statistical multivariate procedure (He et al., 2019).

Based on Umeorah et al. (2019), a copula is said as elliptical copula if it is written in the form:

$$C_X\left(u_1, u_2, \ldots, u_m; \sum\right) = F_{\sum}^{m}\left(F^{-1}(u_1), \ldots, F^{-1}(u_m)\right) \tag{3}$$

where $F_{\sum}^{m}$ is m-dimensional multivariate distribution, $\sum$ is correlation matrix, and F^{-1} is inverse of univariate distribution.

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1.1. Gaussian Copula

The Gaussian Copula is denoted by $C_\rho^{\sum}(u)$ and it can be written as:

$$C_\rho^{\sum}(u) = \frac{1}{2\pi\sqrt{|\sum|}} \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_2)} \left(-\frac{x_1^2 - 2\rho x_1 x_2 + x_2^2}{|\sum|}\right)^{-\frac{\beta+2}{2}} dx \tag{4}$$

where $\boldsymbol{u} = (u_1, u_2), \boldsymbol{x} = (x_1, x_2), \rho \in (-1, 1)$ is the correlation parameter in $\sum$, Φ^{-1} is inverse of univariate standard normal distribution (Umeorah et al., 2019).

1.2. Students t-Copula

The Students t-Copula is quite similar as gaussian copula. It is denoted by $C_{\rho,\beta}^{\sum}(u)$ and it can be written as:

$$C_{\rho,\beta}^{\sum}(u) = \frac{1}{2\pi\sqrt{|\sum|}} \int_{-\infty}^{t_\beta^{-1}(u_1)} \int_{-\infty}^{t_\beta^{-1}(u_2)} \left(1 + \frac{x_1^2 - 2\rho x_1 x_2 + x_2^2}{\beta\,|\sum|}\right)^{-\frac{\beta+2}{2}} dx \tag{5}$$

where $\boldsymbol{u} = (u_1, u_2)$, $\boldsymbol{x} = (x_1, x_2)$, $\rho \in (-1, 1)$ is the correlation parameter in $\sum$, t_β^{-1} is inverse of student t-distribution with degree of freedom β (Umeorah et al., 2019).

2. Archimedean Copula

A copula is said as archimedean copula if it is written in the form:

$$C_X(u_1, u_2, \ldots, u_m) = \phi^{-1}(\phi(u_1) + \ldots + \phi(u_m)) \tag{6}$$

where $\phi(x)$ is the generator of copula and it should be satisfied these conditions:

- $\phi(0) = \infty$ and $\phi(1) = 0$
- ϕ^{-1} is the inverse function and it corresponds to a probability, $\phi^{-1} : [0, \infty] \to [0, 1]$
- $\phi(x)$ is decreasing and convex, $x \in [0, \infty)$

The Archimedean copula is a symmetric copula function (Li and Hou, 2022). There are three family of Archimedean Copula. The generator and bivariate copula function of those Archimedean Copulas is shown in Table 1.

Table 1. The Family of Archimedean Copulas

Family	Generator $\varnothing(u)$	Bivariate Copulas $C(u_1, u_2)$
Clayton	$\theta^{-1}\left(u^{-\theta} - 1\right), \theta \in [0, \infty)$	$\left(u_1^{-\theta} + u_2^{-\theta} - 1\right)^{\frac{1}{\theta}}$
Gumbel	$(-\log(u))^\theta, \theta \in [1, \infty)$	$\exp\left\{-1\left[(-\log(u_1))^\theta + (-\log(u_1))^\theta\right]^{\frac{1}{\theta}}\right\}$
Frank	$\log\left[\left(e^{\theta t} - 1\right)\left(e^\theta - 1\right)^{-1}\right], \theta \in (-\infty, \infty)$	$\frac{1}{\theta}\log\left(1 + \frac{\left(e^{\theta u_1} - 1\right)\left(e^{\theta u_2} - 1\right)}{e^\theta - 1}\right)$

Based on (Karakas et al., 2017), Tau Kendall could be use to estimate the parameter of Archimedean Copula. The link of each Archimedean Copula and Tau Kendall is :

Clayton :

$$\tau = \frac{\theta}{\theta + 2}, \theta \in [0, \infty) \tag{7}$$

Gumbel :

$$\tau = \frac{\theta - 1}{\theta}, \theta \in [0, \infty) \tag{8}$$

Frank

$$\tau = 1 - \frac{1}{\theta}\left[1 - D_J(\theta)\right], \theta \in (-\infty, \infty) \tag{9}$$

where D is Debye function :

$$-D_J(\theta) = \int_{t=0}^{1} \frac{\left[\ln(1 - t^\theta)\right](1 - t^\theta)}{(t^{\theta - 1})} \tag{10}$$

3. Coral Reefs in Indonesia and Sea Surface Temperature (SST) Anomalies

Coral reefs are ecosystems of habitats that are made by parget-producing marine biota, especially by coral animals, together with other biota that live on the seabed and in the water column. Determination of the status of coral reefs in Indonesia was claimed by the Oceanographic Research Center - Indonesian Institute of Sciences data, in accordance with the Decree of the Head of the Geospatial Information Agency No.54 year 2015 which established the Indonesian Institute of Sciences as the data for the field of coral reef ecosystems and sea grass ecosystems (Giyanto et al., 2017).

Sea surface temperature (SST) is the temperature of the top millimeter of the surface of ocean. When something is different from normal or average, it is called anomaly. SST anomaly is how different the sea temperature at a specific location at a specific time is from the normal temperatures for that place (Przyborski and Levy, 2022).

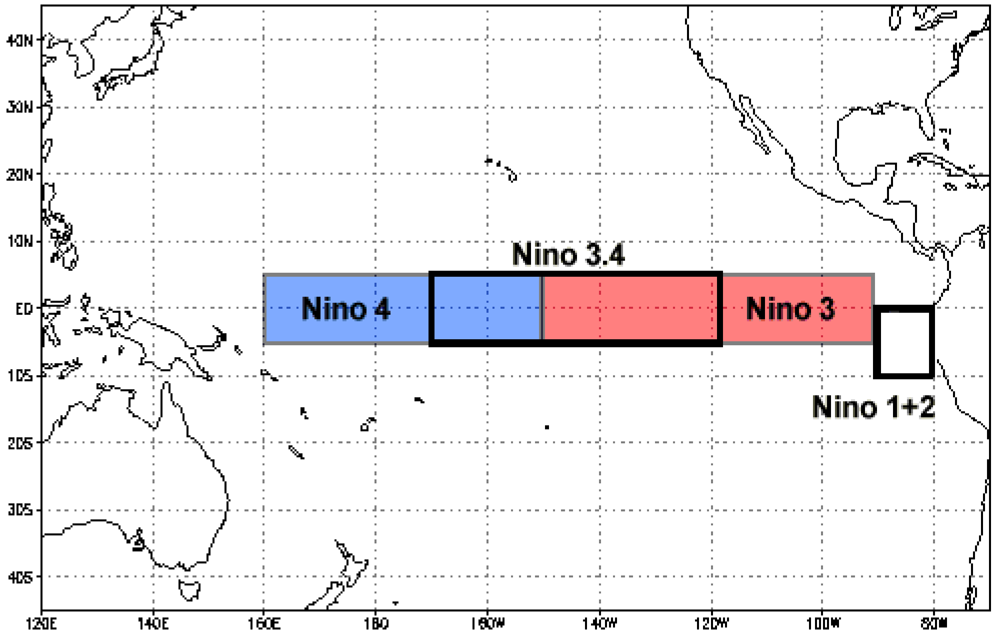

Figure 1. The Division of Nino
Source :https://www.ncei.noaa.gov/access/monitoring/enso/sst

Based on National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information, SST anomalies are divided into four, namely SST Nino 1 + 2, Nino 3, Nino 4, and Nino 3.4 anomalies. The scientists have classified the intensity of El Nio based on SST anomalies exceeding a pre-selected threshold in a certain region of the equatorial Pacific. The division of Nino based on its limits is explained in Figure 1. We can say that SST Nino 4 is nearest Nino to Indonesia.

B. RESEARCH METHOD

In this study, researchers studied the relationship between the coral reefs damage condition and climate change in the three of Indonesian coral reefs regions: West, Central and East Indonesia, by using Copula analysis. The data of coral reefs damage condition used is the percentage data of coral reefs in each study area that has bad/damaged status (live coral cover 0-25%) from COREMAP - The Indonesian Institute of Sciences (http://coremap.oseanografi.lipi.go.id/). While climate change data used is Sea Surface Temperature (SST) anomalies, including SST Nino 1+2, Nino 3, Nino 3.4, and Nino 4 anomaly from NOAA National Weather Service Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/CDB/). Those data are collected from 1999 until 2017. The research variable is presented in Table 2:

Table 2. The Research Variable

Variable	**Scale**
Percentage of Coral Reefs in Damage Condition	Ratio
SST Nino 1+2 Anomaly	Ratio
SST Nino 3 Anomaly	Ratio
SST Nino 3.4 Anomaly	Ratio
SST Nino 4 Anomaly	Ratio

The first step of analysis is preprocessing data. Following that, we did correlation analysis on the percentage of coral reefs in damage condition and each of SST anomalies. After we obtained the result of correlation analysis, then we did copula analysis to obtain the relationship. We used gaussian, clayton, gumbel and frank copula in the analysis. As written in literature review in (Umeorah et al., 2019), the copula analysis is divided into several steps. First, we transformed all the data into Uniform [0,1] domain. Once we got the transformed data, we did scatterplot analysis on the transformed data of percentage of coral reefs in damage condition and each of SST anomalies. Then we estimated Copula parameter using Tau Kendall approach in R software. After that, we found the significance parameters of Copulas, then we should choose the best Copula that could represent the relationship of coral reefs damage and SST anomalies. The best copula is copula that has the highest log likelihood value. Once the best copula is selected, we can conclude how is the relationship of coral reefs damage and SST anomalies in each region.

The research flow chart can be seen in Figure 2:

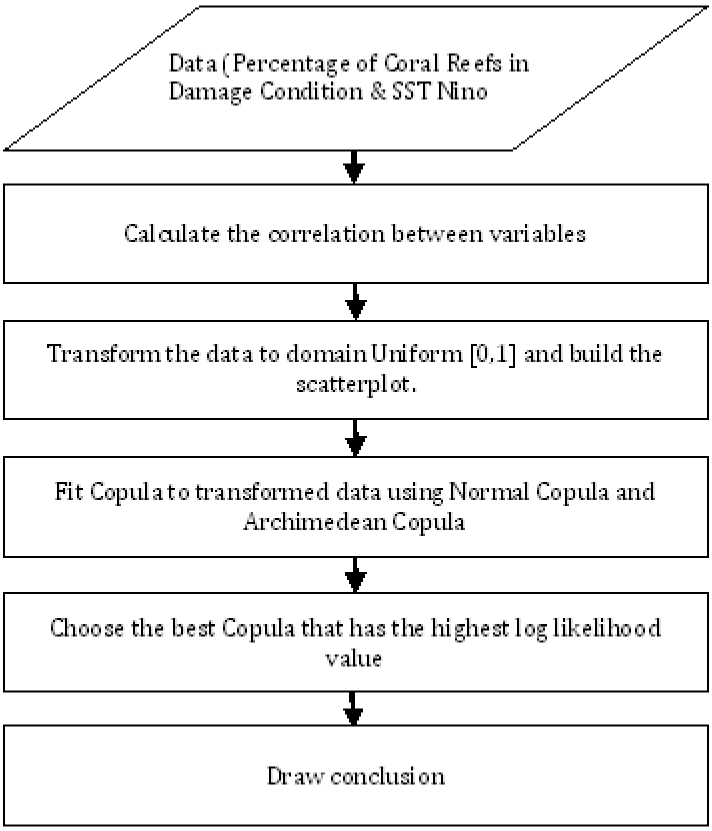

Figure 2. The Research Flow Chart

C. RESULTS AND DISCUSSION

Correlation analysis was done before we use Copula to analyze the relationship between the percentage of coral reefs in damage condition and SST anomalies in the three Indonesian coral reefs regions. The correlation analysis results indicated that the percentage of coral reefs in damage condition in West and Central Indonesia do has correlation with SST anomalies, while the percentage of coral reefs damage condition in East Indonesia does not correlate with any of SST anomalies. From those results, we continue to analyze the case by using Copula and R software. Both of Elliptical Copula (gaussian) and Archimedean Copulas was used in analysis, because the result of distribution test said that some of the data was normally distributed and some was not, then one best Copula will be selected as implementation of the result.

The data used in Copula analysis is transformed data that has domain in Uniform [0,1]. The Scatterplot of transformed data in West Indonesia region is shown in Figure 2. That scatterplot indicates that the observation points are close to each others. That condition is also happen for data in Central region, but it is not happen in East region. From the scatterplot, we can say that there is relationship between the two variables (the percentage of coral reefs in damage condition and SST anomalies) in West and Central region. But we still include the East region data for analysis.

Copula analysis was done for all of the data in each region by using R software and we used Tau Kendall approach to estimate Copula parameter. The results of Copula parameter estimation in each region of coral reefs in Indonesia is shown in Table 3.

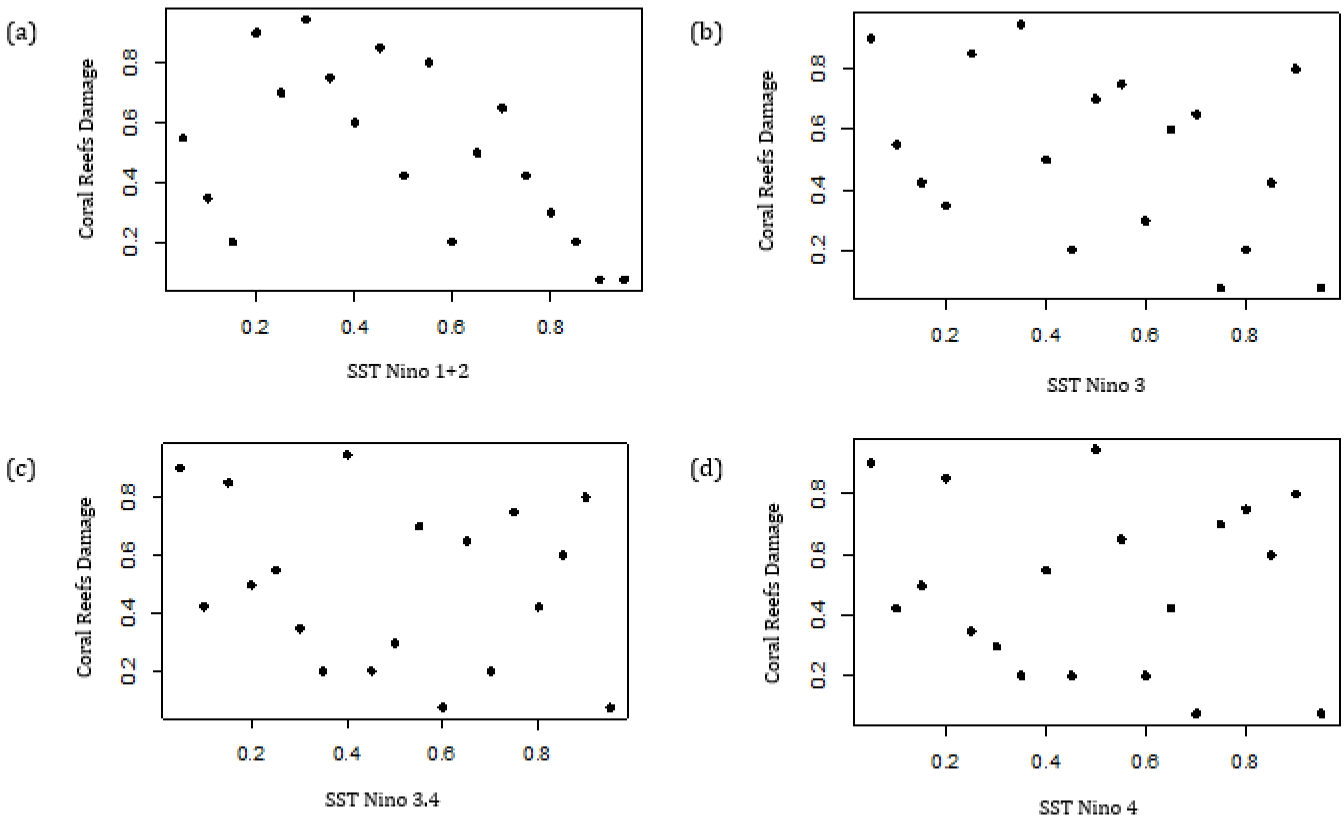

Figure 3. The Scatterplot of Transformed Data [0.1] of Percentage of Coral Reefs Damage in West Region and SST Nino 1+2 (a); Nino 3 (b); Nino 3.4 (c); Nino 4 (d)

Table 3 shows that almost of Gumbel Copula parameters can not be estimated. Thats condition was happened because the parameter calculated is lower than 1, whereas the Copula parameter should be at $[1, \infty)$. The Clayton, Frank and Gaussian Copula parameters for SST Nino 4 and the percentage of coral reefs in damage condition in West Region are significant at the 0.05 level; in Central Region, the Clayton Copula parameter for SST Nino 1+2 and the Frank Copula Parameter for SST Nino 4 are significant with and the percentage of coral reefs in damage condition; while there are no significance parameter for the relationship of both variables in East Region. We can conclude that coral reefs damage condition in East Indonesia does not have relationship with any of SST Nino anomalies.

Table 3. The Copula Parameter Estimation

Variable	Copula	West Region		Central Region		East Region	
		Parameter	P-Value	Parameter	P-Value	Parameter	P-Value
SST Nino 1+2 anomaly and Percentage of Coral Reefs in Damage Condition	Clayton	-0.58	0.83	0.31*	0.04	-0.06	0.74
	Gumbel	-	-	1.16	0.07	-	-
	Frank	-4.21	0.47	1.23	0.06	-0.28	0.74

	Gaussian	-0.59	0.55	0.21	0.06	-0.05	0.71
SST Nino 3 anomaly and Percentage of Coral Reefs in Damage Condition	Clayton	-0.38	0.86	-0.34	0.18	-0.13	0.99
	Gumbel	-	-	-	-	-	-
	Frank	-2.24	0.51	-1.94	0.09	-0.62	0.96
	Gaussian	-0.36	0.62	-0.32	0.09	-0.11	0.97
SST Nino 3.4 anomaly and Percentage of Coral Reefs in Damage Condition	Clayton	-0.27	0.39	-0.51	0.28	-0.13	0.66
	Gumbel	-	-	-	-	-	-
	Frank	-1.42	0.15	-3.42	0.1	-0.62	0.57
	Gaussian	-0.24	0.19	-0.51	0.11	-0.11	0.57
SST Nino 4 anomaly and Percentage of Coral Reefs in Damage Condition	Clayton	-0.15*	0.04	-0.56	0.16	-0.15	0.72
	Gumbel	-	-	-	-	-	-
	Frank	-0.75*	0.02	-4.05*	0.04	-0.73	0.54
	Gaussian	-0.13*	0.02	-0.58	0.07	-0.13	0.56

* parameter is significant at the 0.05 significance level

Table 4. Model Fitting Copula in West Region of Indonesia

Variables	Copula	Parameter	Log Likelihood	P-Value
SST Nino 4 anomaly and Percentage of Coral Reefs in Damage Condition	Clayton	-0.15	0.47	0.06
	Frank	-0.83	0.12	0.04
	Gaussian	-0.32*	0.47	0.01

* the highest log likelihood value and parameter is significant at the 0.05 significance level

Table 5. Model Fitting Copula in Central Region of Indonesia

Variables	Copula	Parameter	Log Likelihood	P-Value
SST Nino 1+2 anomaly and Percentage of Coral Reefs in Damage Condition	Clayton	0.31	0.01	0.07
SST Nino 4 anomaly and Percentage of Coral Reefs in Damage Condition	Frank	-4.89*	3.26	0.01

* the highest log likelihood value and parameter is significant at the 0.05 significance level

The next step is selecting the best Copula in West and Central Region by using Maximum Likelihood Estimation. This method is based on the value of log likelihood. The best Copula is the one that has the highest value of log likelihood and the parameter is proved significant at the 0.05 level.

Table 4 shows that the best Copula that represents the relationship between SST Nino 4 and the percentage of coral reefs in damage condition in West Region is Gaussian Copula. It has the highest value of log likelihood (log likelihood = 0.47) and the parameter is significant at 0.05 level (p-value = 0.01). The Gaussian Copula parameter is -0.32. The interpretation of this Copula is the same as Pearson Correlation. Because the parameter is negative value, we can conclude that the higher the value of SST Nino 4 anomaly, the lower the percentage of coral reefs damage condition in the West Region of Indonesia, and otherwise. While in Central region, as we can see in Table 5, the best Copula is Frank Copula. It represents the relationship between SST Nino 4 and the percentage of coral reefs in damage condition. It has the highest log likelihood value that is 3.26, and it also has significance parameter (p-value = 0.01). The Frank Copula parameter is -4.89. The Frank Copula is one of Archimedean Copulas that does not have tail dependency. We can say that the SST Nino 4 and the percentage of coral reefs in damage condition in Central Region of Indonesia has low correlation.

The result of this study confirms that coral reef ecosystems damage in Indonesia and SST anomalies has relationship. By using Copula method, that relationship could be presented in parameter, called Copula parameter. This parameter (as mentioned in analysis before) give some explanation of the relationship, whether how the higher or the smaller the value of SST Nino can affect coral reef ecosystems damage. This interpretation is not found yet in the previous researches of the relationship of coral reef ecosystems damage in Indonesia and SST anomalies. The previous studies, Speers et al. (2016) and Susiloningtyas et al. (2018), are concluding that there is relationship of coral reef ecosystems damage and climate change or it can be noted that the climate change has impact on the damage of coral reefs ecosystem, but it cannot be explained which what climate change index that has relationship with the damage of coral reef and how the relationship is. While in the results of this study, beside we confirm that there is relationship of coral reef ecosystems damage and climate change index, that is SST anomalies, we also obtain which SST anomalies that has relationship with coral reef damage, and we determine a value (called Copula parameter) that can explain how the relationship is.

D. CONCLUSION AND SUGGESTION

The aim of this study is to indicate the relationship between coral reef ecosystems damage in Indonesia and SST anomalies based on Copula method that is not been used yet in the previous studies. In this study, by using Copula method, beside we confirm that there is relationship of coral reef ecosystems damage and SST anomalies, we also obtain a Copula parameter that can explain how the relationship of ecosystems damage and SST anomalies is. The results indicate that SST Nino 4 is the one SST Nino anomaly that has relationship with the percentage of coral reefs in damage condition in West and Central Region of Indonesia. The Copula represents the relationship between SST Nino 4 and the percentage of coral reefs in damage condition in West Region is Gaussian Copula (parameter = -0.32). It indicates that the higher the value of SST Nino 4 anomaly, the lower the percentage of coral reefs damage condition in the West Region of Indonesia, and otherwise. The Copula that represents the relationship between SST Nino 4 and the percentage of coral reefs in damage condition in Central Region is Frank Copula (parameter = -4.89). We can say that the SST Nino 4 and the percentage of coral reefs in damage condition in Central Region of Indonesia has low correlation. Those results roots to the location of SST Nino 4 that is the nearest to Indonesia. However, the coral reefs damage condition in East Indonesia does not have relationship with any of SST Nino anomalies. It also shown in the first correlation analysis before. For the future research, it is highly recommended for using the last update data of percentage of coral reefs in damage condition in all region of Indonesia and SST anomalies to the analysis.

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