Persistence of high sea surface temperature (> 30°C) in Tomini Bay

Aprilia Da Cruz Tita, Anindya Wirasatriya, Denny N Sugianto, Lilik Maslukah, Gentur Handoyo, Hariyadi, Muhammad Helmi and Praditya Avianto

1Department of Oceanography, Faculty of Fisheries and Marine Science, Universitas Diponegoro, Jl. Prof. Sudharto SH, Tembalang, Semarang, Indonesia.
2Center for Coastal Disaster Mitigation and Rehabilitation Studies, Universitas Diponegoro, Semarang Indonesia.
3Research Center for Oceanography, Indonesian Institute of Science

*Corresponding author: apriliacruz20@gmail.com

Abstract. Hot Event is a phenomenon with high sea surface temperature > 30°C, which can influence the global climate. Tomini Bay which is categorized as the semi-enclosed waters have the daily appearance of SST >30°C. The purpose of this research is to investigate and determine the mechanism for the occurrence of high and constant SST (>30°C) in Tomini Bay. We found that the phenomenon of constant high SST (> 30°C) in Tomini Bay is influenced by the weak wind speed by less than 4 m/s. The existence of Sulawesi topography and the Togian Islands block the incoming wind and reduce the wind speed. Moreover, the percentage of SST (>30°C) in the middle of Tomini Bay higher than in the western area of Tomini Bay. This might be influenced by the shallow bathymetry in the middle of the Tomini Bay which increases the effectiveness of the heating process in this area.

1. Introduction

One of the oceanographic parameters that form the basis for air-sea interactions is sea surface temperature (SST) of the sea. Air-sea interactions in areas with high SST are important in the global climate system [1]. The phenomenon with a high sea surface temperature of more than 30°C is called Hot Event (HE), which is influential in regulating global climate variability. Hot events occur only in conditions of high solar radiation and weak wind speeds. For SST 20 - 29.5°C, the increase of SST increase the cloud formation. In contrast, after 29.5°C, the rising SST is followed by decreasing cloud formation. This phenomenon indicates that to reach SST more than 30°C, clear sky condition is needed. Furthermore, the frequency occurrence for SST > 30°C decreases significantly which indicates that this condition rarely happens due to the special condition of the clear sky which is mentioned previously [2].

The Hot Event in the western Pacific Ocean was strongly influenced by the presence of small islands which create weak wind regions [3]. Indonesia is an archipelagic country consists of more than
17,000 Islands. Moreover, Indonesia is also located in the equator which makes the sun shines throughout the year. Thus, the high SSTs may frequently be generated within Indonesia Seas. One area that is potential for Hot Event study in Tomini Bay. Tomini Bay is semi-enclosed water located in Sulawesi Island, surrounded by mountain ranges and connected to the Maluku Sea (Fig. 1). The persistent high SST is investigated in the present study.

Figure 1. Study area. Background color is SST Climatology in Tomini Bay (2003 - 2015). Inset map is Indonesia

2. Methodology

2.1. Data

We use optimal spatial and temporal interpolation data called New Generation Sea Surface Temperature version 2.0a (NGSST-O-Global-V2.0a) daily and 0.1° × 0.1° for SST [6]. Standard periods used from 2003 to 2015. Sea Surface Temperature version 2.0a (NGSST-O-Global-V2.0a) is a dataset of SST observations made by two satellite sensors with microwave sensors in the form of (Advanced Microwave Scanning Radiometer for Earth Observing) System (AMSR-E) and WindSat [7], while for infrared sensor satellites in the form of Advanced Very High-Resolution Radiometers (AVHRR) that are high in the NOAA-POES series (Polar Orbiting Environmental Satellites) and Moderate Resolution Imaging Spectroradiometers (MODIS) on Aqua and Terra [5]. Surface winds that are obtained from the Cross-Calibrated Multi-Platform (CCMP) are a combination of surface wind data derived from conventional sources (ship observation) and in situ (buoys) and several satellites (QuikSCAT, ADEOS-II, AMSR-E, TRMM TMI and SSM/I) into global analysis that is close to consistent with a resolution of 25 km resolution of 0.25° x 0.25° every 6 hours [8] for 2003 to 2015 and accessed from http://noaa.gov. Surface flow data with a resolution of 0.083° x 0.083° from www.marinecopernicus.com. integrates land topography and ocean bathymetry (https://www.ngdc.noaa.gov/mgg/global/). Topography was obtained from Global 30 Sond-Elevation Arc (GTOPO30) (https://lta.cr.usgs.gov/GTOPO30) while bathymetry was obtained fromETOPO, a 1-
minute global aid model surface of the earth that integrates soil topography and marine bathymetry (https://www.ngdc.noaa.gov/mgg/global/).

2.2. Method

The parameters of SST, wind, currents and solar radiation are compiled on a monthly basis and monthly climatology uses formulas [9]:

\[ \bar{X}(x, y) = \frac{1}{n} \sum_{i=1}^{n} x_i(x, y, t) \]  

(1)

where \( \bar{X}(x, y) \) is the monthly climatology value at position \((x, y)\), \(x_i(x, y, t)\) is the \(i\)-value of the data at \((x, y)\) position and time \(t\). Next, \(n\) is the amount of data in a period of 1 month and the amount of monthly data in 1 climatology period (i.e., from 2003 to 2015 = 13 data) for monthly calculations and monthly climatology calculations, respectively. Furthermore, \(x_i\) is not included in the calculation if the pixel is an empty pixel.

To find out the distribution and value of SST and annual wind or climatology (for 13 years) in general, the daily average data of SST and wind are processed using the following formula [9] :

\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  

(2)

to get a high percentage of SST (> 30\(^\circ\)C) and weak wind <4 m/s in Tomini Bay which aims to determine the highest value of SST and weak winds in facilitating the identification of this high SST phenomenon in percent in general, then the data is average daily processed using equation (3) to get the percentage with the following formula:

\[ \% = \frac{1}{n} \sum_{i=1}^{n} y_i \times 100\% \]  

(3)

where \(\%\) is the percentage of high SST more than 30\(^\circ\)C or percentage of weak wind speed less than 4 m/s, and \(y_i\) is the amount of SST data more than 30\(^\circ\)C and the amount of weak wind speed less than 4 m/sec, \((x, y)\) is the monthly climatology value at position \((x, y)\), \(x_i(x, y, t)\) is the \(i\)-value of the data at \((x, y)\) position and time \(t\). Then, \(n\) is the amount of data in a period of 1 month and the amount of monthly data in 1 climatology period (i.e., from 2003 to 2015 = 13 data) for monthly calculations and monthly climatology calculations, respectively.

3. Results and discussion

3.1. Seasonal variation of SST in Tomini Bay

First, we show the climatology of SST in Tomini Bay from 2003 to 2015 (Fig.1). The SST climatology in Tomini Bay is more than 30\(^\circ\)C. In tropical seas, regions with Sea Surface Temperature (SST) above 28\(^\circ\)C are referred to as warm pools, which have implications for atmospheric processes [5]. It has been shown that the minimum SST needed for active convection is 28\(^\circ\)C. The phenomenon of high SST >30\(^\circ\)C in the Tomini Bay occurs almost every day while for the phenomenon of the Hot Event itself does not occur more than two months. High SST events >30\(^\circ\)C that are constant in Tomini Bay are unique phenomena, therefore this research needs to be done so that it can be further examined the mechanisms of this phenomenon.
We plot SST climatology in Tomini Bay for illustrating the seasonal variability of SST in Tomini Bay for 13 years. Based on Figures 2 and 3 for four seasons followed by climatology of wind and surface currents. It is seen that the SST in Tomini Bay experienced a rise in temperature during the Transition I and Transition II seasons and a decrease in SST during the West and East seasons. This is caused by the influence of the monsoon blowing.

The high value of SST in the Transition I season (March-May) with SST 30°C - 32°C. While, Transition Season II (September - November) with SST 29.5°C - 31°C and low SST in the West season (December - February) with SST 29.5°C - 31°C, and East season (June - August) with SST 29.5°C - 31°C closely related to differences in wind pattern movements. The movement of the wind direction in the West Season is predominantly heading to the southeast because the sun is in the Southern Hemisphere (BBS) so the BBS receives more solar radiation than the Northern Hemisphere (BBU) and causes the high-pressure center above the Asian continent while the center of pressure is low is on the continent of Australia. Wyrtki [10] stated that in December to February, namely in the winter at BBU the sun is in the position of 23.5 Selatan South Latitude, the high-pressure center is in North Asia. In this condition, the wind blows from the northeast then when it passes through the equator this wind is deflected because of the influence of the earth's rotation and becomes the northwest wind above Indonesia and blows towards the low-pressure center on the Australian Continent.

Wind movement in the East season is more dominant in the southwest. This is because this season the sun is at BBU so that the northern hemisphere receives more solar radiation than BBS and causes the high-pressure center to be above the Australian continent while the low-pressure center is above the Asian continent. According to [10] states that from June to August, namely in the winter on the sun BBS is in the position of 23.5° North Latitude, the high-pressure center is in Australia. The wind blows from the Australian Continent then as it passes through the equator the wind turns from the southwest towards the northeast through the western part of Indonesia towards the low-pressure center in North Asia.
The Transition I Season, which is a transition between the West Season to the East Season, which is shown in the March-May period, shows that the wind pattern changes direction, the wind blows from the west/southwest to the north/north northwest (Fig. 2b). According to [10] This is due to a shift in the position of solar radiation from the BBS to the equator so that the center of high and low-pressure changes. Transition Season II from the East Season to the West Season begins in September, where the position of the sun begins to move towards the equator. The Transition II Season is characterized by winds that begin to change direction, from the northwest to the northeast. The change and deflection of the wind are also caused by the Coriolis force due to the rotation of the earth so that winds in the Northern Hemisphere (BBU) will be deflected to the right and those in the Southern Hemisphere (BBU) are turned left. Although in theory if the wind speed is weak then SST increases and vice versa, but in Tomini Bay the average wind speed <4 m/s is seen in Figure 4 so that there is no significant recall.

Surface currents generated by wind influence the mass distribution of water [11]. Water mass distribution affects SST. Wind power has an influence on surface currents around 2% of the wind speed itself. This current velocity will decrease according to the increasing depth of the water until finally, the wind has no effect at a depth of 200 meters [12]. The movement of the surface flow pattern of the West Season moves speed which tends to be stronger than the Transition I season, which tends to be weaker. Even though the velocity tends to be weak but the direction changes, this affects the mixing process of the seawater vertically to be weak and the heat lost through evaporation decreases. This situation has an impact on the high sea surface temperature [13]. The East season the current velocity tends to be stronger and its movement towards the northwest/north, while the Transition II Season flows slowly begins to weaken and its movement towards the northwest/north.
3.2. High SST in study areas of Tomini Bay

For time series analysis, we extracted the mean values of SST and wind speed in areas A and B as shown in Fig. 4. Area A and B represent the area inside and outside Tomini Bay, respectively. Sea Surface Temperature (SST) in the study area B shown in Figure 6a ranges from 29°C while for study area A the sea surface temperature is more than 30°C. The percentage of SST >30°C in region B is 20%, which
means that the incidence of SST > 30°C is very rare and does not even occur at all, whereas region A with 50% - > 80% means that the SST is > 30°C almost every day happened for 13 years. The SST difference between the study area B and the study area A was due to the influence of weak wind speeds in the region. It can be seen in Figure 5 that in both the study areas A and B when the wind speed weakens, the SST increases and vice versa. In Figure 7, it is explained that region B has a strong wind speed of > ± 4 m / s while region A is ± 1 m/s, meanwhile Figure 7b explains that the study area B has less than 80% percent of weak wind 4 m/s, meaning that this area is very rarely passed by winds that blow with speed 4 m/s and vice versa, region A with more than 90%.

Figure 5. Time series of monthly climatology of SST and Wind in Study Areas A and B in Tomini Bay

Figure 6. a) Average SST Climatology (2003 - 2015), b) Percentage of Weak Winds <4m/s, c) Percentage of SST> 30°C (2003-2015)
The difference in wind speed seen in Figure 7 is influenced by the topographic influence of Sulawesi Island. The study area B is located outside the Tomini Bay, when the wind blows past the great wind friction because the topography around the study area B in the north end of Sulawesi Island is 800 m and the seas of study area B are more open than region A so the wind speed is strong. As a result, sea surface temperatures in the study area B are lower than others. The study area A which is located in the Tomini Bay is semi-enclosed surrounded by highlands in the north, west, and east with an altitude of 800 m and the Togian Islands in the middle of Tomini Bay so that the wind will pass the area will be blocked and experience friction because of the rudeness of the earth. Friction force causes weakening wind speed [14]. Weak wind speed events that influence the difference in SST between regions A and B are explained through Figure 8 that overall the wind speed weakens in the West season while in the East season the wind speed gets stronger.

The low sea surface temperature in the study area B besides being influenced by velocity factors is also caused by the upwelling phenomenon around the region B so that the SST in region B is lower than the region A. The upwelling phenomenon carries cold water mass from deep layer below to the surface. This is evidenced by research conducted by [15] that upwelling phenomena occur in the eastern part of Tomini Bay which makes SST outside the Tomini Bay is lower than SST inside Tomini Bay.

Next, we show the incongruity of the relationship between SST and wind speed in area A. We divide area A into area A1 and A2. The high SST between the A1 and A2 regions seen from the graph plot results in Figure 8 shows that the SST in the study area A2 is higher than the A1 study area, wind speed is weaker in the A1 region than in the A2 region. According to [2] weak wind speeds makes SST higher. This supports A2 region having lower SST than A1, but the results show that A1 region has lower SST. The percentage of weak winds is less than 4 m/s in Figure 6b, the study area A1 is greater than the study area A2 with a value of more than 90%. This means that the influence of weak winds on the value of SST in Tomini Bay occurs almost every day and has a very large effect on SST in Tomini Bay. The percentage of SST > 30°C shown in Figure 6a shows that, in the study area A2 has the largest percentage of more than 80%, the A1 study area is ± 50%. The high and constant percentage of sea surface temperature in the A2 study area shows that sea surface temperatures in the region with values > 30°C occur almost every day for a period of 13 years, from 2003 to 2015. A1 study area shows that sea surface temperature events > 30°C for 13 years in general is not always the case.

According to [16], it is explained that mountains on land (upland) affect sea surface temperatures. Wind movement in the East season in August, in the southern part of Tomini Bay, the wind moves from the south with a speed of 5 m/s over Sulawesi Island and study area A, the weakening wind speed to 2 - 3 m/s to the northwest. The B wind study area moves from the south to the north at a speed of 6 m/s and passes through the small island in the south and weakens to 5-5.5 m/s. The study
area B has a lower temperature of 27°C - 28°C while region A has a temperature of > 30°C. Topography plays a role in the strength of the wind blowing in the formation of high and constant temperatures in the study area A.

Based on CTD data in Tomini Bay seen in Figure 9, it explains that the study areas A1 and A2 have the same characteristic of water masses. Station 9 which represents the A1 area and stations 7, 8, 10, 11 and 12 representing the A2 area change in the thermocline layer for the temperature seen in Figure 10 and the halocline for salinity seen in Figure 9 but returns homogeneous again as depth increases. According to [17], it is explained that the thermocline layer which is also referred to as the transition layer has a characteristic temperature gradient that is a change in temperature to a depth of 0.1°C for every one meter depth increase, whereas according to [17] the halocline layer is a layer with a large relative salinity change. The solar radiation factor shown in Figure 10 shows that the concentration of solar radiation in the two study areas is similar, so it does not affect the SST phenomenon. This is because the distribution of latent heat release is related to the distribution of wind speed. In areas where wind speeds are strong, latent heat release is also high. The average latent heat release variation closely related to variations in wind speed [18]. In Tomini Bay which has a weak wind speed affects the latent heat to be low too.

Figure 8. Graph of SST vs Wind in the A1 and A2 Study Areas in Tomini Bay
The constant difference in sea surface temperature in the area of study area A2 is thought to occur due to the influence of bathymetry (Figure 11c). According to [17] other factors that influence water temperature are bathymetry. The state of bathymetry in Figure 11c shows that the study area A1 and A2 of Tomini Bay have different morphological and bathymetric characteristics. The study area A2 has shallow bathymetry of less than 400 m, while for areas A1 it has shallow bathymetry around the land and deep waters in the middle part with a depth of about 2000 m. The shallow area in the A2 area results in less volume of water compared to those in area A1 so that the heating process that occurs in the A2 area is faster and more effective than the A1 area. Rapid heating in area A2 makes SST in this area higher and constant compared to area A1. However this indication still should be examined further by analyzing the heat budget in the water column. This work is left for future study.
4. Conclusions

Based on the results obtained in this study, it can be concluded as follows:

1. The monthly climatological variation in the distribution of the highest and constant Sea Surface Temperature in the Tomini Bay region occurs in the Transition I season with a range of SST 30°C - 32°C and the lowest in the West season with SST 29.5°C - 31°C and in other seasons namely Transition II season with a range of SST 29.5°C - 31°C and East seasons with SST 29.5°C - 31.5°C.

2. a) Sea Surface Temperature (SST) phenomenon is high > 30°C and constant in study area A with respect to study area B due to the influence of weak wind speeds of less than 4 m/s in region A compared to region B because of the topography of Sulawesi Island and Islands Togian thus weakens wind speed and the upwelling phenomenon around area B which causes low SST.

b) Sea Surface Temperature (SST) is high > 30°C and constant that occurs in the study area A2 is higher than the A1 region which is affected by weak wind speed factors < 4 m/s in the A1 compared to A2 region may be related to bathymetry regions in the region A2 which is categorized as shallow water. Thus, the process of heating water masses in the A2 region is faster than the A1 region.

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