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Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

GES Submission Acknowledgement

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Kepada: "Abd. Rasyid Jalil" <abdulrasyid.fayufi@gmail.com>

Dear Abd. Rasyid Jalil:

Thank you for submitting the manuscript, "CENDRAWASIH HOT POOL: STUDY OF THE HIGH-FREQUENCY OCCURRENCE OF HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA" (ID 2652) to GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY. With the online journal management system that we are using, you will be able to track its progress through the editorial process by logging in to the journal web site:

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Abd. Rasyid Jalil[1,*], Anindya Wirasatriya[2,3], Fatwa Ramdani[4], Abdul Malik[5], Puji Rahmadi[6], Gentio Harsono[7], Riza Yuliratno Setiawan[8]

[1]Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Indonesia
[3]Coastal and Ocean Remote Sensing Laboratory, Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University, Indonesia
[4]Faculty of Computer Science, Brawijaya University, Malang Indonesia
[5]Department of Geography, Faculty of Mathematics and Natural Science, Universitas Negeri Makassar, Indonesia
[6]Research Center for Oceanography, Indonesian Institute of Science, Jakarta, Indonesia
[7]Faculty of Defense Technology Republic Indonesia, Indonesia Defense University, Jakarta, Indonesia
[8]Department of Fisheries, Gadjah Mada University, Yogyakarta, Indonesia.

***Corresponding author:** Abd. Rasyid Jalil, E-mail: abdulrasyid.fayufi@gmail.com

CENDRAWASIH HOT POOL: STUDY OF THE HIGH-FREQUENCY OCCURRENCE OF HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA

ABSTRACT. The warm pool has been used to define a water body with the characteristic of SST exceeding 28°C within a particular area and a relatively long period in an annual circle. However, there are regions with an annual mean SST measured above 30°C, and we classified them as Hot Pools because of the conditions of intense solar radiation and low wind speed. One of the Hot Pool spots was found in Indonesia, in Cenderawasih Bay. In the present study, the existence of the Cendrawasih Hot Pool is examined using long-term observation of satellite SST data. We also used surface wind data, surface heat flux, and surface current to investigate their mechanisms. The results show that for more than half a year, SSTs in Cendrawasih Bay can reach more than 30°C. The location is also dominated by low wind speed, i.e., 80% wind speed of fewer than four m/s occurred during 2003-2015, and these caused the low latent loss in Cendrawasih Bay. In surface current, during the dry and wet seasons, Cendrawasih Bay is fully isolated since the easterly subsurface water flow does not enter the bay. The absence of strong currents prevents the mixing process from maintaining the high temperature in the surface layer. Those processes are figured out and become strong evidence to justify Cendrawasih Bay as one of the Hot Pool areas within the Indonesian seas.

KEYWORDS: Global climate; Sea Surface Temperature; Hot Pool Spot; Cendrawasih Bay.

INTRODUCTION

The western equatorial Pacific significantly influences the global climate. The warm pool, a region with average sea surface temperatures (SST) above 28°C, has a specific impact on the Earth's circulation (e.g., Wyrtki 1989; Yan et al. 1992; Clement and Seager 1999; Chongyin et al. 1999; Pierrehumbert 2000; Clement et al. 2005; Thoron et al. 2005; Herweijer et al. 2005).

On the other hand, high sea surface temperature (SST) in tropical regions has attracted researchers to investigate the mechanisms since the formation of high SST requires a particular atmospheric process (e.g., Ramanathan and Collins 1991; Wallace 1992; Arking and Ziskin 1994). This process is depicted by Waliser and Graham (1993), which shows the relation between SSTs and deep convection. They utilized highly reflective cloud information from an arbitrary examination of monthly SST data with a grid spacing of 2° (produced from combined satellite observation and in situ data) and daily visible and infrared satellite image data. The highly reflective cloud increases along with the SST as it rises from 26°C to 29.5°C. In contrast, the highly reflective cloud diminishes with increased SST in the temperature from 29.5°C to 32°C. As a result, the analysis proved that several atmospheric processes impacted SSTs below and above 29.5°C.

By taking advantage of high temporal and spatial resolution sea surface temperature (SST) products derived from satellite observations (i.e., daily and ≤ 25 km×25 km), several studies (Kawamura et al. 2008; Qin et al. 2007, 2008; Qin and Kawamura 2009, 2010; Wirasatriya et al. 2015, 2016, 2017a, 2020) were able to identify high SST events (i.e., more than 30°C) in specific areas and at certain periods and define them as Hot Event (HE). In summary, they concluded that considerable daily heat gains characterize the production of HE under high solar radiation and low wind speed brought on by "remote convection" mechanisms.

Wirasatriya et al. (2015) elaborated on the climatology of HEs in the western equatorial Pacific using the SST dataset derived from satellite microwave sensors. Throughout nine years of observation (2003-2011), they discovered 71 HE cases in the western equatorial Pacific, with the majority centered on the Solomon Islands and New Guinea Island's northern coasts, which extend eastward up to 160°W. According to the climatology, the region is located in an area with solar radiation of more than 200 W/m^2 and wind speeds of less than 4 m/s. Low wind speeds heavily influence the mechanism for HE incidence in the western equatorial Pacific. Much of the equatorial region experiences sun radiation above 200 W/m2 during the HE periods. Low wind speeds minimize latent heat loss, which results in high SSTs and HEs in specific locations. Wirasatriya et al. (2015) also emphasized that high solar radiation and low wind speed are much more common during the development stage and less common during the decay stage. This study also demonstrated that a rise in the long-term mean SST in the western equatorial Pacific is correlated with an increase in the frequency of HE events. HEs were responsible for 51.5% of the SSTs >30°C in the warm pool region bounded by the 29.5 °C isotherms of the climatological SST. Thus, statistically, there is a relation between the occurrence of HE and the formation of the western Pacific warm pool. Moreover, Wirasatriya et al. (2020) demonstrated the role of HE in maintaining the warm mixed layer in the western Pacific warm pool. The frequent occurrence of HE transports heat from the surface layer to the deeper layer above the thermocline.

Within the Indonesian seas, the frequent appearance of high SST > 30°C has been reported by Tita et al. (2020) in Tomini Bay and by Swandiko et al. (2021) in the Malacca Strait. Their appearances also the high solar radiation and weak wind. The morphology of the semi-enclosed waters causes the high-frequency occurrence of low wind speed by less than four m/s in both areas.

In the present study, we demonstrate the constant high SST occurrence (more than 30°C) in Cendrawasih Bay. Cendrawasih Bay is located in northern Papua Island, part of the western Pacific warm pool. It is semi-enclosed water with a deep basin, surrounded by mountain chains (Fig. 1). Cendrawasih Bay is the habitat for whale sharks (Ihsan et al. 2018). Since the area determines warm pool definition with SST climatology higher than 28°C, we call the high-frequency occurrence of SSTs higher than 30°C in the Cendrawasih Bay the Cendrawasih Hot Pool. Wirasatriya et al. (2015) found that the duration of HE occurrence in the western equatorial Pacific is no longer than two months since HE requires a typical condition of high solar radiation and low wind speed. Thus, it is interesting to understand the mechanisms of the high-frequency occurrence of high SST in the Cendrawasih Hot Pool.

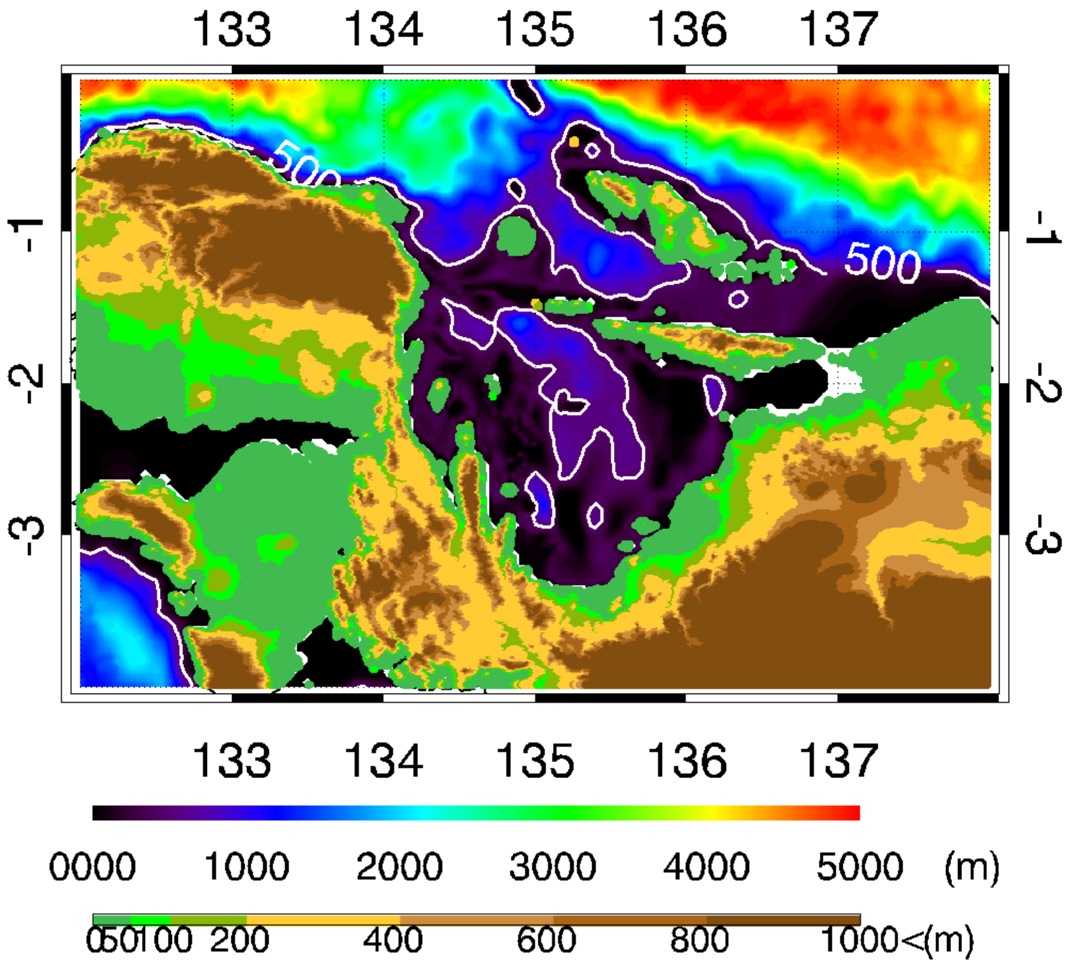

Fig. 1. Bathymetry and topography of Cendrawasih Bay

MATERIALS AND METHODS

We used the semi-daily 11 µm SST products from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua Lv3 with a spatial resolution of 0.04°×0.04° (Esaias et al. 1998) and observation period from 2003 to 2015. The MODIS SST 11µthe Multi-Channel SST algorithm generates m by using brightness temperatures at 11 µm and 12 µm (Brown and Minnet 2009). The best accuracy was achieved by validating and testing this data against in-situ measurements (e.g., Lee et al. 2010; Qin et al. 2014; Ghanea et al. 2015).

We can obtain the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 from the following website: www.remss.com, and use it to calculate surface winds. As a result, CCMP is regarded as a Level-3 ocean vector wind analysis product. They are created utilizing data from moored buoys, satellites, and model winds.

The surface wind data for spatial and temporal resolutions is 0.25°×0.25° respectively and quarter daily. This wind product has greater accuracy than other wind reanalysis data.

We used a 0.5° grid from the Objectively Analyzed Air-Sea Fluxes project to analyze daily latent heat fluxes and solar radiation (Yu and Weller, 2007). The period of observation for latent heat flux is from 2003 to 2015, but for solar radiation is only from 2003 to 2009 due to the availability of the data. Global 30 Arc-Second Elevation data was used to obtain topography. Global 30 Arc-Second Elevation (GTOPO30) data was used to obtain topography (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects). ETOPO, a one-arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry, provides bathymetry (https://www.ngdc.noaa.gov/mgg/global/). The analysis of the current study is based on a climatological feature. To create monthly and monthly climatology, all geophysical parameters are incorporated as follows: (Wirasatriya et al. 2017b)

$$\overline{X}(x,y) = \frac{1}{n}\sum_{i=1}^{n} xi\,(x,y,t) \qquad (1)$$

where $\overline{X}(x,y)$ is monthly mean value or monthly climatology value at position (x,y), $xi(x,y,t)$ is i^{th} value of the data at (x,y) position and time t. Next, n is the number of data in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 13 data) for monthly calculation and monthly climatology calculation, respectively. Moreover, if pixel xi is a hollow pixel, it is not included in the calculation. To look at the relationships between the parameters, we also used correlation analysis

For oceanic parameters, we used the current reanalysis data from http://marine.copernicus.eu/ to obtain the seasonal variation of the current pattern in the Cendrawasih Hot Pool.

RESULTS AND DISCUSSION

Cendrawasih Hot Pool

The definition of the Cendrawasih Hot Pool is described in Fig. 2, which shows the climatological mean of SST and the percentage of daily SSTs more than 30°C from 2003 to 2015 (13 years). In Cendrawasih Bay, the mean SST at the southern part of 2°S is more than 30°C, and the high SSTs are more than 50%. It means that the mean SST in Cendrawasih Bay is higher than the definition of the western Pacific warm pool which is 28°C (Wyrtki 1989), and more than half-year SSTs in Cendrawasih Bay can reach more than 30°C. At the southernmost of the bay, the mean SST reaches 30.5°C, with the percentage of high SSTs being more than 70%. It has become the hottest area of Cendrawasih Bay.

In contrast, in the area outside Cendrawasih Bay, i.e., the western Pacific warm pool's offshore seas, the percentage is less than 30%. Thus, this evidence supports the definition of Cendrawasih Bay as the Cendrawasih Hot Pool. The high-frequency occurrence of high SST in Cendrawasih Bay may correspond to whale sharks' appearance throughout the year. Ihsan et al. (2018) indicated the tolerance of whale sharks in high SST conditions.

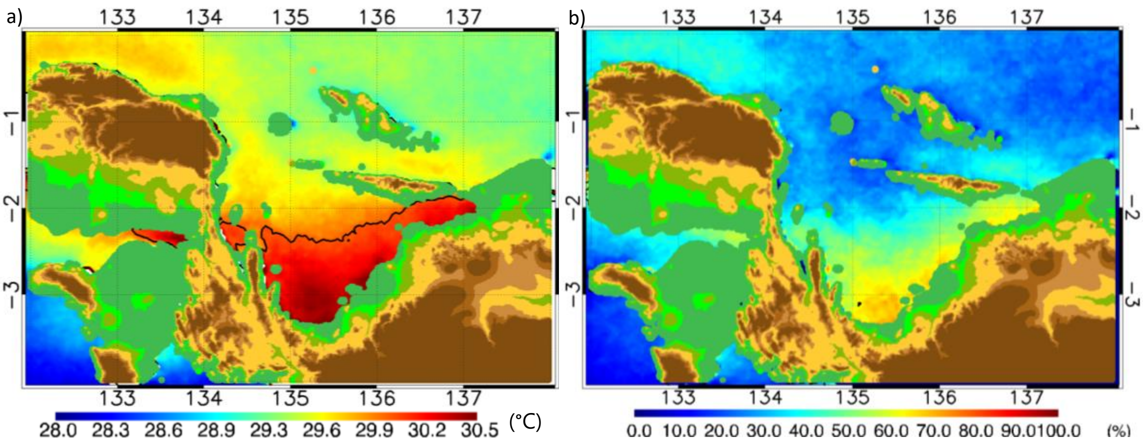

Fig. 2. Climatological mean of SST (a) and Percentage of daily SSTs > 30°C during thirteen years of observation (2003-2015) (b). The black contour is 30°C.

Atmospheric aspect of Cendrawasih Hot Pool

Since high SST of more than 30°C occurs during the condition of low wind speed (i.e., < 4 m/s) and high solar radiation (i.e., > 200 W/m^2) (Wirasatriya et al. 2015), we calculated the percentage of low wind speed and high solar radiation in the Cendrawasih Bay. Furthermore, we also calculated the percentage of low latent heat release to explain how wind speed influences the variability of SST. The result is depicted in Fig. 3, which clearly shows that Cendrawasih Bay is dominated by the condition of low wind speed, i.e., 80% wind speed of fewer than four m/s occurred during 2003-2015. This causes low latent loss in Cendrawasih Bay. For solar radiation, the percentage of high solar radiation inside and outside Cendrawasih Bay is almost similar i.e., nearly 50%, indicating that high solar radiation is not dominant in both areas. This means that, although high solar radiation does not frequently occur, the absence of high wind speed may maintain the latent heat loss to keep the persistence of high SST in Cendrawasih Bay.

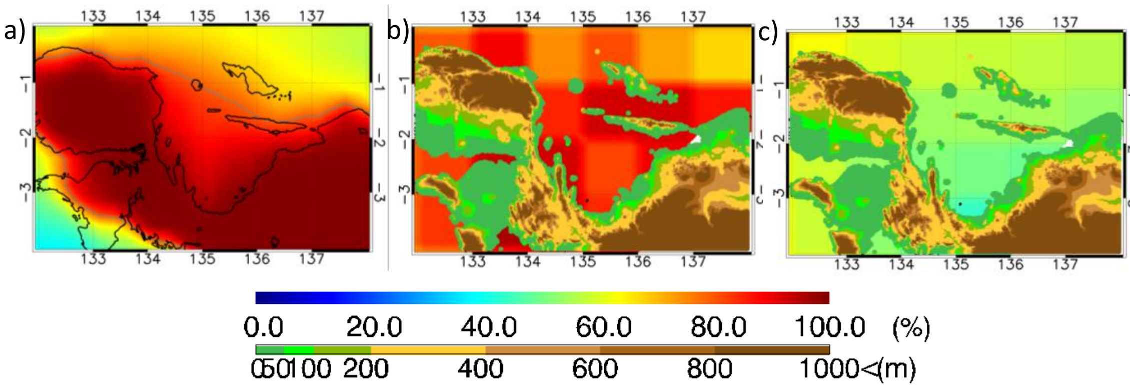

Fig. 3. The percentage of wind speed less than four m/s (a), latent heat release less than 120 W/m^2 (b), and solar radiation more than 200 W/m^2 (c).

To investigate how low wind speed occurs in the study area, we show the monthly climatology map of surface wind during summer and winter (Fig. 4). For both seasons, Cendrawasih Bay is protected from high wind speed due to high mountain chains in the western, southern, and eastern parts. In the northern part, small islands at the mouth of the bay prevent the strong wind speed from entering the bay. Thus, the role of topography is crucial for the occurrence of constant high SSTs in Cendrawasih Bay. The same tendencies are also found at the Tomini Bay and Malacca Strait, as indicated by Tita et al. (2020) and Swandiko et al. (2021).

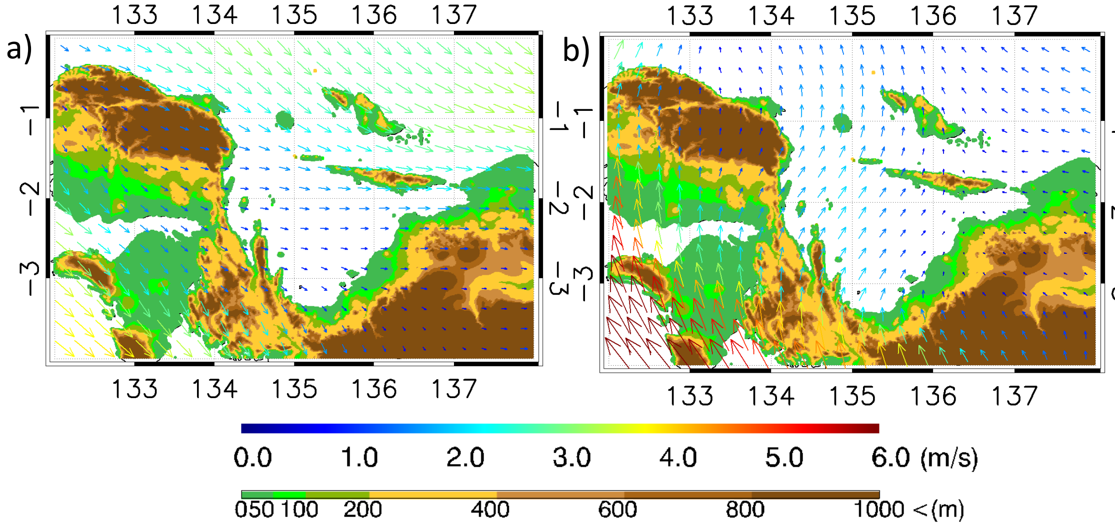

Fig. 4. Monthly climatology of surface wind speed during a) wet season (January) and b) dry season (August)

The oceanic aspect of Cendrawasih Hot Pool

To investigate the oceanic aspect of the Cendrawasih Hot Pool, we plotted the current patterns shown in Fig. 5. A northwestward current has been identified north of Cendrawasih Bay. During the wet season (January), the speed of this current ranges from 0.5 m/s to 0.7 m/s. During the dry season (August), when the northwesterly wind disappears (Fig. 4b), the speed of the northwestward current increases. This northwestward current is known as the New Guinea Coastal Under Current (NGCUC). NGCUC is a permanent current feature at 200 m depth regardless of the wind reversals (Tsuchiya et al. 1989). Inside Cendrawasih Bay, strong currents are absent in this area which prevents the mixing process from maintaining the high temperature in the surface layer. During the dry and wet seasons, Cendrawasih Bay is fully isolated since the easterly subsurface water flow does not enter Cendrawasih Bay. Thus, this isolated basin causes the Cendrawasih Bay area to be influenced mainly by the air-sea interaction process mentioned in the previous section creating Cendrawasih Hot Pool.

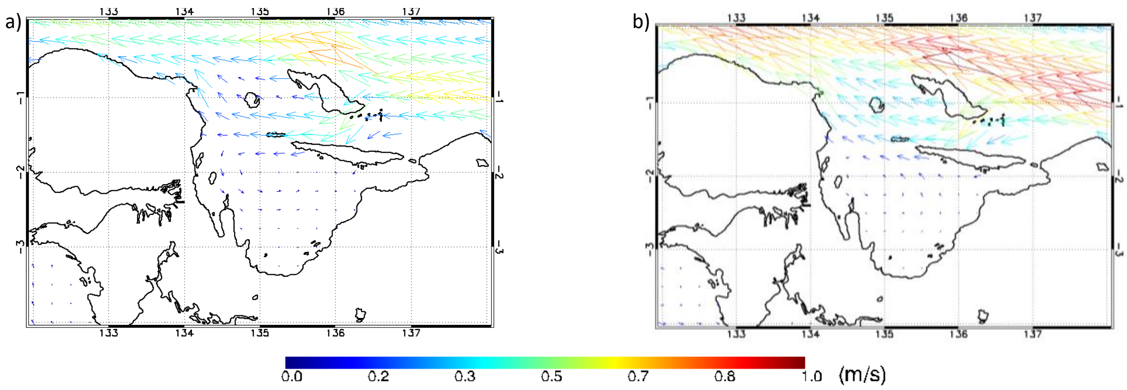

Fig. 5. Monthly climatology of current 100 m in January (a) and August (b)

CONCLUSIONS

The hot Pool is used to categorize high SST episodes (>30^{0}C) in particular areas and during specific periods (relatively long periods). Since the "warm pool" has been used to define an area with the annual average SST distributed below 30^{0}C in dominant, therefore "hot pool" was taken to represent the area with SST dominated above 30^{0}C.

Under high solar radiation and low wind speed, this event is characterized by considerable daily heat gains. The constant high SST occurrence in Cendrawasih Bay, which is more than half a year, SSTs can reach more than 30°C and are dominated by the condition of low wind speed, i.e., 80% wind speed of fewer than four m/s along the years, also solar radiation measured more than 200 W/m^2, those are the solid evidence for define Cendrawasih Bay as the "Cendrawasih Hot Pool."

ACKNOWLEDGMENTS

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Gmail Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

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Dear Dr Abd. Rasyid Jalil!

We have reached a decision regarding your submission to GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY, "CENDRAWASIH HOT POOL: STUDY OF THE HIGH-FREQUENCY OCCURRENCE OF HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA". Our decision is **revisions required.**

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A. Category and general nature of the manuscript:
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Overall, how would you rate this paper?:
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Does the abstract summarize the main points of the paper: purpose, methods, results, conclusion?:
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Are the results clearly explained?:
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Definitely yes

Are there any limitations of the study that should be noted?:
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1. The title is not good, please revise it.
2. Please check through the grammatical error. The sentence structure should be appropriate.
3. Once defined, the acronyms for some words should be used along with the paper. Sometimes the acronyms are directly used, for example SST and so on.
4. Please improve colorbar in Fig 1.
5. It is recommended to introduce research question in the introduction section. Why the HE is important? What is the effect of the HE events on environment?
6. Introduction section needs to be revised and added more previous study to show the gap of knoledge.
7.It is obvious that there are differences between spatial resolution and temporal of datasets, however, are there any effect on results? Please describe it.
8. My major concern consists in the structure of the Methodology description. This would make it more understandable and let ease replication of the procedures.
9. Thirteen years of observation (2003-2015) able to represent the climatology of SST? Why not use data for longer period?
10. Fig. 5 should be improved.
11. It is recommended to add more analysis and results for supporting the conclusion.

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Author's Responses to Reviewer Comments and Suggestions

The paper has the potential to be published after revision.

General Response: Thanks for your suggestion, question, and criticism for improving our manuscript. In this revised version, we have explained the method in more detail, improved figures, and added more analysis of the temporal change of SST, wind speed, and solar radiation. The revised parts are highlighted in yellow.

1. The title is not good, please revise it.
   Response: Thank you very much for the suggestion. We have revised the title to CENDRAWASIH HOT POOL: THE FREQUENT HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA.
2. Please check through the grammatical error. The sentence structure should be appropriate.
   Response: Thank you very much for the comment. We have carefully checked the grammar. Hopefully, this revised version is better.
3. Once defined, the acronyms for some words should be used along with the paper. Sometimes the acronyms are directly used, for example SST and so on.
   Response: Thank you very much for the correction. We have fixed it.
4. Please improve colorbar in Fig. 1
   Response: The colorbar in Fig 1 has been improved.
5. It is recommended to introduce research question in the introduction section. Why the HE is important? What is the effect of the HE events on environment?
   Response: Thank you very much for the recommendation. We have added more explanation to describe how HE has an important role in regulating global climate through its contribution to Pacific warm pool formation. L87-96
6. Introduction section need to needs to be revised and added more previous study to show the gap of knowledge.
   Response: Thank you very much for the suggestion. The knowledge gap in this study is that there are few studies about the high SST phenomena within the Indonesian seas. (L97-101). We have emphasized the gap at L101-102.
7. It is obvious that there are differences between spatial resolution and temporal of dataset, however, are there any effect on results? Please describe it.
   Response: Thank you very much for the question. The spatial resolution differs among datasets, but this is OK since the analysis is not based on the grid-by-grid analysis. Descriptively we compare the spatial distribution of all datasets and then take the mean values in 2 areas as a sample for investigating the temporal variation. Solar radiation differs from others for the observation period since the dataset was only available in 2009. But we think this is OK since the same method is applied by Wirasatriya et al. (2015, 2016, 2020), Tita et al. (2020), and Swandiko et al. (2021)
8. My major concern consists in the structure of the Methodology description. This would be more understandable and let ease replication of the procedures.

Response: Thank you very much for the suggestion. We have described the methodology clearer than before.

9. Thirteen years of observation (2003-2015) able to represent the climatology of SST? Why notuse data for longer period?
   Response: Thank you very much for the question. We follow the period of observation by Wirasatriya et al. (2015, 2016, 2020), Tita et al. (2020), and Swandiko et al. (2021)
10. Fig. 5 should be improved.
    Response: Thank you very much for the suggestion. It is done.
11. It is recommended to add more analysis and results to support the conclusion
    Response: Thank you very much for the suggestion. We have added the analysis of the temporal change of SST, wind speed, and solar radiation in the area inside and outside Cenderawasih Bay (Fig. 5, L214-237)

Abd. Rasyid Jalil[1*], Anindya Wirasatriya[2,3], Fatwa Ramdani[4,5], Abdul Malik[6], Puji Rahmadi[7], Gentio Harsono[8], Riza Yuliratno Setiawan[9]

[1]Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Indonesia
[3]Coastal and Ocean Remote Sensing Laboratory, Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University, Indonesia
[4]Department of International Public Policy, Faculty of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[5]Program in Economic and Public Policy, Graduate School of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[6]Department of Geography, Faculty of Mathematics and Natural Science, Universitas Negeri Makassar, Indonesia
[7]Research Center for Oceanography, Indonesian Institute of Science, Jakarta, Indonesia
[8]Faculty of Defense Technology Republic Indonesia, Indonesia Defense University, Jakarta, Indonesia
[9]Department of Fisheries, Gadjah Mada University, Yogyakarta, Indonesia.

***Corresponding author:** Abd. Rasyid Jalil, E-mail: abdulrasyid.fayufi@gmail.com

CENDERAWASIH HOT POOL: THE FREQUENT HIGH SST PHENOMENA AT CENDERAWASIH BAY, PAPUA

ABSTRACT. The warm pool has been used to define a water body with the characteristic of SST exceeding 28°C within a particular area and a relatively long period in an annual circle. However, there are regions with an annual mean SST measured above 30°C, and we classified them as Hot Pools because of the conditions of intense solar radiation and low wind speed. One of the Hot Pool spots was found in Indonesia, in Cenderawasih Bay. ~~In the present study, the existence of the Cendrawasih Hot Pool is examined~~The present study examines the existence of the Cenderawasih Hot Pool using long-term observation of satellite SST data. We also used surface wind data, surface heat flux, and surface current to investigate their mechanisms. The results show that within 13 years of observation (2013-2015), SSTs in Cenderawasih Bay can reach more than 30°C with 50% occurrence within the ~~period of observation~~observation period. Heat input comes from strong solar radiation, i.e., 50% of solar radiation is more than 200 W/m^2. The location is also dominated by low wind speed, i.e., 80% wind speed of lower than 4 m/s, ~~and these~~which caused the low latent loss in ~~Cendrawasih~~Cenderawasih Bay. ~~For surface current, Cendrawasih Bay is fully isolated~~Cenderawasih Bay is fully isolated for surface currents during the dry and wet seasons~~,~~ since the easterly subsurface water flow does not enter the bay. The absence of strong currents prevents the mixing process, maintaining the high temperature in the surface layer. Those processes are figured out and become strong evidence to justify ~~Cendrawasih~~Cenderawasih Bay as one of the Hot Pool areas within the Indonesian seas.

KEYWORDS: Global climate; Sea Surface Temperature; Hot Pool Spot;

~~Cendrawasih~~Cenderawasih Bay.

INTRODUCTION

The western equatorial Pacific significantly influences the global climate. The warm pool, a region with average sea surface temperatures (SST) above 28°C, has a specific impact on the Earth's circulation (e.g., Wyrtki 1989; Yan et al. 1992; Clement and Seager 1999; Chongyin et al. 1999; Pierrehumbert 2000; Clement et al. 2005; Thoron et al. 2005; Herweijer et al. 2005).

On the other hand, high SST in tropical regions has attracted researchers to investigate the mechanisms since the formation of high SST requires a particular atmospheric process (e.g., Ramanathan and Collins 1991; Wallace 1992; Arking and Ziskin 1994). This process is depicted by Waliser and Graham (1993), which shows the relation between SSTs and deep convection. They utilized highly reflective cloud information from an arbitrary examination of monthly SST data with a grid spacing of 2° (produced from combined satellite observation and in situ data) and daily visible and infrared satellite image data. The highly reflective cloud increases along with the SST as it rises from 26°C to 29.5°C. In contrast, the highly reflective cloud diminishes with increased SST in the temperature from 29.5°C to 32°C. As a result, the analysis proved that several atmospheric processes impacted SSTs below and above 29.5°C.

By taking advantage of high temporal and spatial resolution SST products derived from satellite observations (i.e., daily and ≤ 25 km×25 km), several studies (Kawamura et al. 2008; Qin et al. 2007, 2008; Qin and Kawamura 2009, 2010; Wirasatriya et al. 2015, 2016, 2017a, 2020) were able to identify high SST events (i.e., more than 30°C) in specific areas and at certain periods and define them as Hot Event (HE). In summary, they concluded that considerable daily heat gains characterize the production of HE under high solar radiation and low wind speed brought on by "remote convection" mechanisms.

Wirasatriya et al. (2015) elaborated on the climatology of HEs in the western equatorial Pacific using the SST dataset derived from satellite microwave sensors. Throughout nine years of observation (2003-2011), they discovered 71 HE cases in the western equatorial Pacific, with the majority centered on the Solomon Islands and New Guinea Island's northern coasts, which extend eastward up to 160°W. According to the climatology, the region ~~is located in an area with~~has solar radiation of more than 200 W/m^2 and wind speeds of less than 4 m/s. Low wind speeds heavily influence the mechanism for HE incidence in the western equatorial Pacific. Much of the equatorial region experiences sun radiation above 200 W/m2 during the HE periods. Low wind speeds minimize latent heat loss, which results in high SSTs and HEs in specific locations. Wirasatriya et al. (2015) also emphasized that high solar radiation and low wind speed are much more common during the development stage and less common during the decay stage. This study also demonstrated that a rise in the long-term mean SST in the western equatorial Pacific is correlated with an increase in the frequency of HE events. HEs were responsible for 51.5% of the SSTs >30°C in the warm pool region bounded by the 29.5 °C isotherms of the climatological SST. Thus, statistically, there is a relation between the occurrence of HE and the formation of the western Pacific warm pool. Moreover, Wirasatriya et al. (2020) demonstrated the role of HE in maintaining the warm mixed layer in the western Pacific warm pool. The frequent occurrence of HE transports heat from the surface layer to the deeper layer above the thermocline to maintain the warm mixed layer in the warm pool. Since the Pacific warm pool influences the ~~variability of the global climate through the process of~~global climate's variability through coupled ocean-atmosphere dynamics and thermodynamics (e.g., Clement and Seager 1999; Herweijer et al. 2005), this becomes an example of the contribution of high SST phenomena to regulate the global climate.

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Within the Indonesian seas, the frequent appearance of high SST > 30°C has been reported by Tita et al. (2020) in Tomini Bay and by Swandiko et al. (2021) in the Malacca Strait. Their appearances also the high solar radiation and weak wind. The morphology of the semi-enclosed waters causes the high-frequency occurrence of low wind speed by less than 4 m/s in both areas. Besides these two areas, there is no more study on the high SST phenomena within the Indonesian Seas.

~~In the present study, we demonstrate~~The present study demonstrates the frequent high SST occurrence (more than 30°C) in ~~Cendrawasih~~Cenderawasih Bay. ~~Cendrawasih~~Cenderawasih Bay is ~~located~~ in northern Papua Island, part of the western Pacific warm pool. It is semi-enclosed water with a deep basin, surrounded by mountain chains (Fig. 1). ~~Cendrawasih~~Cenderawasih Bay is the habitat for whale sharks (Ihsan et al. 2018). Since the area determines warm pool definition with SST climatology higher than 28°C, we call the high-frequency occurrence of SSTs higher than 30°C in the ~~Cendrawasih~~Cenderawasih Bay the ~~Cendrawasih~~Cenderawasih Hot Pool. Wirasatriya et al. (2015) found that the duration of HE occurrence in the western equatorial Pacific is no longer than two months since HE requires a typical condition of high solar radiation and low wind speed. Thus, it is interesting to understand the mechanisms of the high-frequency occurrence of high SST in the ~~Cendrawasih~~Cenderawasih Hot Pool.

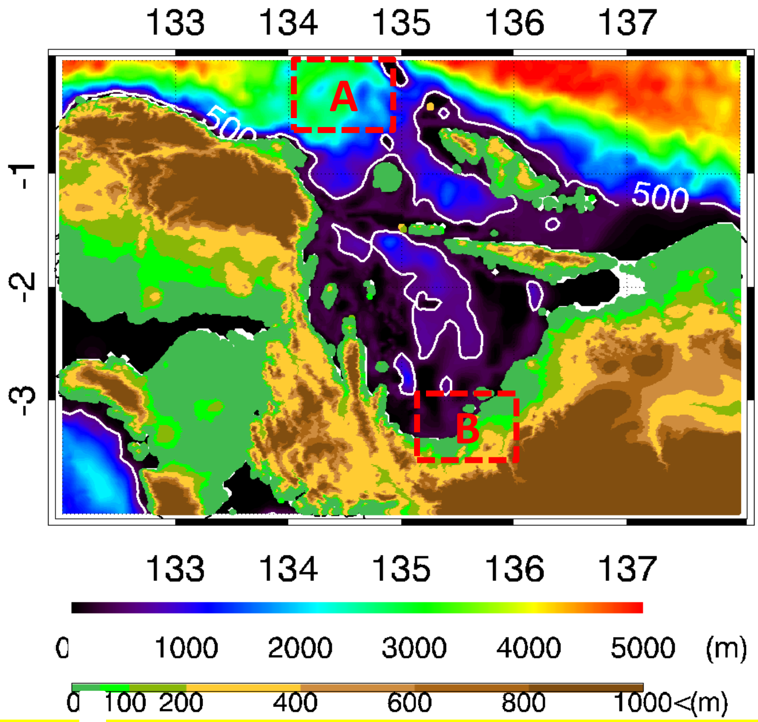

Fig. 1. Bathymetry and topography of ~~Cendrawasih~~Cenderawasih Bay. The dashed boxes A~~,~~ and B represent the sampling area for outside and inside ~~Cendrawasih~~Cenderawasih Bay, respectively, as shown in Fig. 5.

MATERIALS AND METHODS

We used the semi-daily 11 µm SST products from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua Lv3 with a spatial resolution of 0.04°×0.04° (Esaias et al. 1998) and observation period from 2003 to 2015. The MODIS SST 11µthe Multi-Channel SST algorithm generates m by using brightness temperatures at 11 µm and 12 µm (Brown and Minnet 2009). The best accuracy was achieved by validating and testing this data against in-situ measurements (e.g., Lee et al. 2010; Qin et al. 2014; Ghanea et al. 2015).

We can obtain the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 from the following website: www.remss.com, and use it to calculate surface winds. As a result, CCMP is regarded as a Level-3 ocean vector wind analysis product. They are created utilizing data from moored buoys, satellites, and model winds. The surface wind data for spatial and temporal resolutions is 0.25°×0.25° respectively and quarter daily. This wind product has greater accuracy than other wind reanalysis data.

We used a 0.5° grid from the Objectively Analyzed Air-Sea Fluxes project to analyze daily latent heat fluxes and solar radiation (Yu and Weller, 2007). The period of observation for latent heat flux is from 2003 to 2015, but for solar radiation is only from 2003 to 2009 due to the availability of the data. Global 30 Arc-Second Elevation data was used to obtain topography. Global 30 Arc-Second Elevation (GTOPO30) data was used to obtain topography (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects). ETOPO, a one-arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry, provides bathymetry (https://www.ngdc.noaa.gov/mgg/global/). For oceanic parameters, we used the current reanalysis data from http://marine.copernicus.eu/ to obtain the seasonal variation of the current pattern at 100 m depth in the ~~Cendrawasih~~Cenderawasih Hot Pool.

To calculate the frequency occurrence of SST within 13 years of observation, we calculate the percentage of SST > 30°C occurrence in each grid. Since high SST of more than 30°C occurs during the condition of low wind speed (i.e., < 4 m/s) and high solar radiation (i.e., > 200 W/m^2) (Wirasatriya et al. 2015), we calculated the percentage of low wind speed and high solar radiation in the ~~Cendrawasih~~Cenderawasih Bay. Furthermore, we also calculated the percentage of low latent heat release (<120 W/m^2) to explain how wind speed influences the variability of SST. The equation ~~of~~ for calculating the percentage is as follows:

$$\%(x,y) = \frac{1}{n}\sum_{i=1}^{n} pi\,(x,y) \times 100\% \qquad (1)$$

where $\%(x,y)$ is percentage the percentage of high SST > 30°C or percentage of weak wind speed < 4 m/s or percentage of solar radiation > 200 W/m^2 or percentage of latent heat flux < 120W/m^2 at position (x,y); pi is the amount of SST data > 30°C or the amount of weak wind speed < 4 m/sec or the amount solar radiation > 200 W/m^2 or the amount of latent heat flux < 120W/m^2 at position (x,y). Furthermore, we also analyze the climatological mean of each parameter. To create monthly and monthly climatology, all geophysical parameters are incorporated as follows: (Wirasatriya et al. 2017b)

$$\overline{X}(x,y) = \frac{1}{n}\sum_{i=1}^{n} xi\,(x,y,t) \qquad (2)$$

where $\overline{X}(x,y)$ is monthly mean value or monthly climatology value at position (x,y),

$xi(x, y, t)$ is i^{th} value of the data at (x,y) position and time t. Next, n is the number of data in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 13 data) for monthly calculation and monthly climatology calculation, respectively. Moreover, if pixel xi is a hollow pixel, it is not included in the calculation.

RESULTS AND DISCUSSION

~~Cendrawasih~~Cenderawasih Hot Pool

The definition of the ~~Cendrawasih~~Cenderawasih Hot Pool is described in Fig. 2, which shows the climatological mean of SST and the percentage of daily SSTs more than 30°C from 2003 to 2015 (13 years). In ~~Cendrawasih~~Cenderawasih Bay, the mean SST at the southern part of 2°S is more than 30°C, and the high SSTs are more than 50%. It means that the mean SST in ~~Cendrawasih~~Cenderawasih Bay is higher than the definition of the western Pacific warm pool which is 28°C (Wyrtki 1989),~~,~~ and ~~totally~~ more than 3.5 years within 2003-2015, SSTs in ~~Cendrawasih~~Cenderawasih Bay can reach more than 30°C. At the southernmost of the bay, the mean SST reaches 30.5°C, with the percentage of high SSTs being more than 70%. It has become the hottest area of ~~Cendrawasih~~Cenderawasih Bay.

In contrast, in the area outside ~~Cendrawasih~~Cenderawasih Bay, i.e., the western Pacific warm pool's offshore seas, the percentage is less than 30%. Thus, this evidence supports the definition of ~~Cendrawasih~~Cenderawasih Bay as the ~~Cendrawasih~~Cenderawasih Hot Pool. The high-frequency occurrence of high SST in ~~Cendrawasih~~Cenderawasih Bay may correspond to whale sharks' ~~appearance throughout the year~~yearly appearance. Ihsan et al. (2018) indicated the tolerance of whale sharks in high SST conditions.

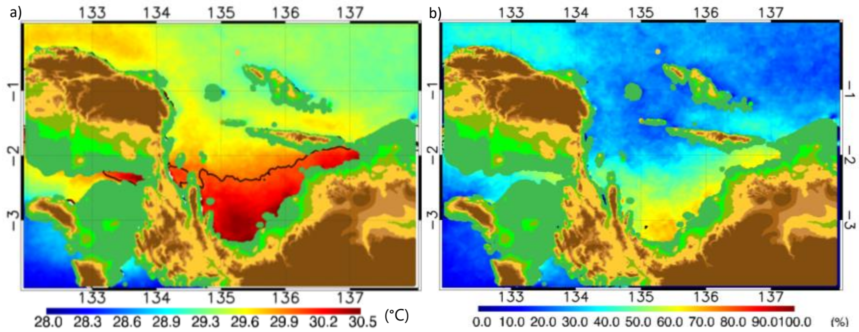

Fig. 2. Climatological mean of SST (a) and ~~Percentage~~ percentage of daily SSTs > 30°C during thirteen years of observation (2003-2015) (b). The black contour is 30°C.

Atmospheric aspect of ~~Cendrawasih~~Cenderawasih Hot Pool

Fig. 3 clearly shows that ~~Cendrawasih~~ low wind speed dominates Cenderawasih Bay ~~Bay is dominated by the condition of low wind speed~~, i.e., 80% wind speed < 4 m/s occurred during 2003-2015. This causes low latent loss in ~~Cendrawasih~~Cenderawasih Bay. For solar radiation, the percentage of high solar radiation inside and outside ~~Cendrawasih~~Cenderawasih Bay is almost similar i.e., nearly 50%, indicating that high solar radiation is not dominant in both areas. This means that, although high solar radiation does not frequently occur, the absence of strong wind speed may maintain the latent heat loss to keep the SST in ~~Cendrawasih~~Cenderawasih Bay higher than 30°C.

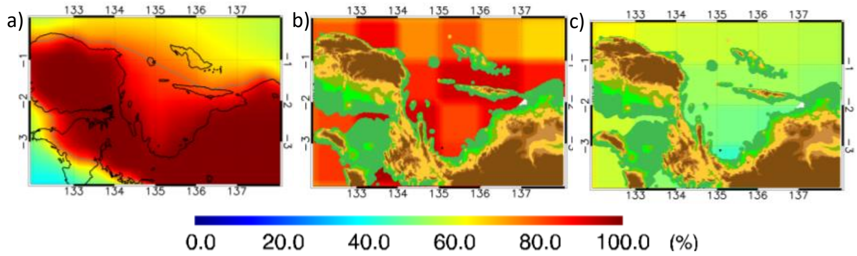

Fig. 3. The percentage of wind speed less than four m/s (a), latent heat release less than 120 W/m^2 (b), and solar radiation more than 200 W/m^2 (c).

To investigate how low wind speed occurs in the study area, we show the monthly climatology map of surface wind during summer and winter (Fig. 4). For both seasons, ~~Cendrawasih~~Cenderawasih Bay is protected from high wind speed due to high mountain chains in the western, southern, and eastern parts. In the northern part, small islands at the mouth of the bay prevent the strong wind speed from entering the bay. Thus, the role of topography is crucial for the occurrence of constant high SSTs in ~~Cendrawasih~~Cenderawasih Bay. The same tendencies are also found at the Tomini Bay and Malacca Strait, as indicated by Tita et al. (2020) and Swandiko et al. (2021).

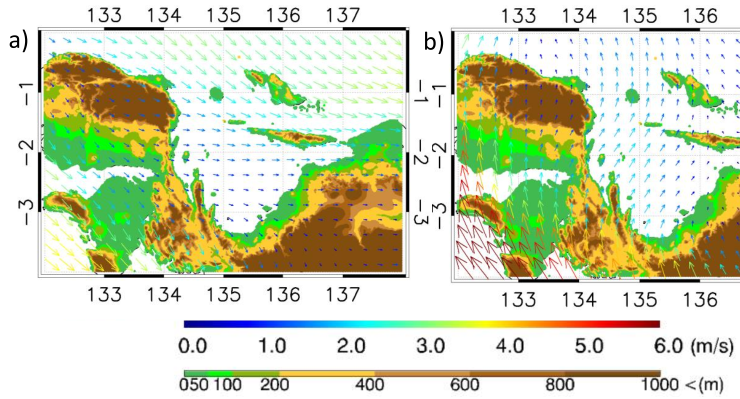

Fig. 4. Monthly climatology of surface wind speed during a) wet season (January) and b) dry season (August)

The influence of wind speed and solar radiation on the SST variation is further examined by plotting the monthly climatology of wind speed, solar radiation, and SST at ~~the area A, and B,~~areas A and B (Fig. 1) that represent the areas outside and inside ~~Cendrawasih~~Cenderawasih Bay. Seasonal variations of SSTs are observed in both areas~~, t~~. The minimum SSTs occur during the wet and dry seasons, while the maximum SSTs during the transition season. This seasonal SST variability is similar ~~with~~ to the other areas in the Indonesian seas, such as the Java Sea (Wirasatriya et al. 2018), Maluku Sea (Wirasatriya et al. 2019), Halmahera Sea (Setiawan et al. 2019), etc.

For the area outside ~~Cendrawasih~~Cenderawasih Bay, SST ranges from 28.2°C to 30.6°C. It is ~~clearly~~ seen that the variability of SST is controlled by wind speed and solar radiation. From January to June, when wind speed decreases from 2.2 m/s to 0.3 m/s and solar radiation is more than 200 W/m^2, SST increases from 28.2°C to 30.5°C. From June to October, wind speed is lower than 1 m/s. In the absence of strong wind, the low SST in July is caused by the decrease of solar radiation ~~in~~to a minimum.

For the area inside ~~Cendrawasih~~Cenderawasih Bay, persistent high SST is observed as the SST ranges from 30.2°C to 31.1°C. It may be due to the low wind speed of~~This may due to the low wind speed that is less than 1 m/s almost throughout~~ fewer than 1 m/s for years. Thus, the variability of SST is ~~clearly~~ seen as ruled by solar radiation. The minimum ~~SST in July is caused by the minimum solar radiation~~solar radiation causes the minimum SST in July. However, the absence of strong wind prevents latent heat loss that maintains the high SST inside ~~the Cendrawasih~~Cenderawasih Bay.

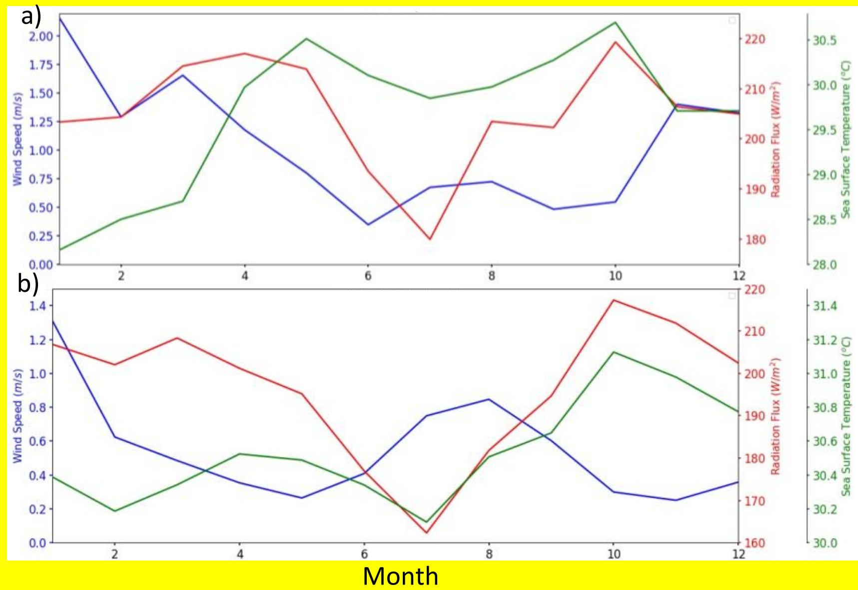

Fig. 5. Monthly climatology of SST, wind speed, and solar radiation at a) area outside and b) area inside ~~Cendrawasih~~Cenderawasih Bay, as shown in Fig. 1.

The oceanic aspect of ~~Cendrawasih~~Cenderawasih Hot Pool

To investigate the oceanic aspect of the ~~Cendrawasih~~Cenderawasih Hot Pool, we plotted the current patterns at 100 m depth shown in Fig. 6. A northwestward current has been identified north of ~~Cendrawasih~~Cenderawasih Bay. During the wet season (January), the speed of this current ranges from 0.5 m/s to 0.7 m/s. During the dry season (August), when the northwesterly wind disappears (Fig. 4b), the speed of the northwestward current increases. This northwestward current is known as the New Guinea Coastal Under Current (NGCUC). NGCUC is a permanent current feature at 200 m depth regardless of the wind reversals (Tsuchiya et al. 1989). Inside ~~Cendrawasih~~Cenderawasih Bay, strong currents are absent in this area~~ which prevents~~, preventing the mixing process from maintaining the high temperature in the surface layer. During the dry and wet seasons, ~~Cendrawasih~~Cenderawasih Bay is fully isolated since the westward subsurface water flow does not enter ~~Cendrawasih~~Cenderawasih Bay. Thus, this isolated basin causes the

CendrawasihCenderawasih Bay area to be influenced mainly by the air-sea interaction process mentioned in the previous section creating CendrawasihCenderawasih Hot Pool.

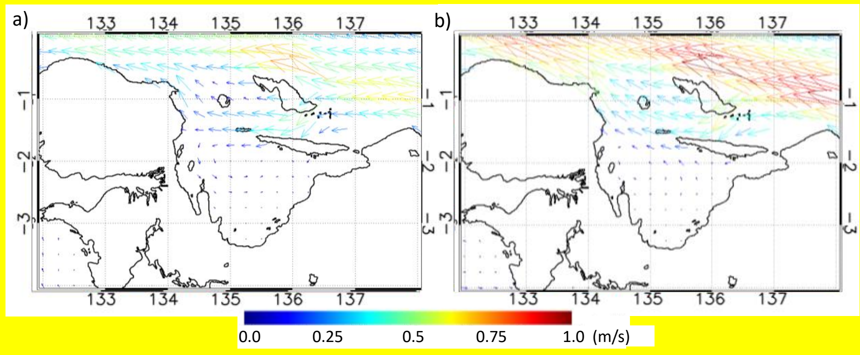

Fig. 6. Monthly climatology of current at 100 m depth in January (a) and August (b)

CONCLUSIONS

The hot Pool is used to categorize high SST episodes (>30^{0}C) in particular areas and during specific periods (relatively long periods). Since the "warm pool" has been used to define an area with the annual average SST distributed below 30^{0}C in dominant, therefore "hot pool" was taken to represent the area with SST dominated above 30^{0}C.

Under high solar radiation and low wind speed, this event is characterized by considerable daily heat gains. The constant high SST occurrence in CendrawasihCenderawasih Bay, which is more than 50% of 13 years, SSTs can reach more than 30°C and are dominated by the condition of low wind speed, i.e., 80% wind speed is less than m/s along the years, also 50% solar radiation measured is more than 200 W/m^2. The current pattern at 100 m depth also shows that NGCUC does not enter CendrawasihCenderawasih Bay. Thus, this indicates that CendrawasihCenderawasih bay is an isolated water. Those are the solid evidence for defining CendrawasihCenderawasih Bay as the "CendrawasihCenderawasih Hot Pool."

ACKNOWLEDGMENTS

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Gmail

Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

GES Editor Decision

Иванов Владимир Владимирович <vladimir.ivanov@aari.ru> 11 Maret 2023 pukul 19.31
Kepada: abdulrasyid fayufi <abdulrasyid.fayufi@gmail.com>

Dear Dr Abd. Rasyid Jalil ,

I have received revised version of your manuscript and I will sent it to the reviewer shortly.

Kind regards,
Vladimir Ivanov

От: "abdulrasyid fayufi" <abdulrasyid.fayufi@gmail.com>
Кому: "Иванов Владимир Владимирович" <vladimir.ivanov@aari.ru>
Копия: "GES Journal" <ges-journal@geogr.msu.ru>
Отправленные: Суббота, 11 Март 2023 г 0:16:48
Тема: Re: GES Editor Decision
[Kutipan teks disembunyikan]

Gmail

Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

GES Editor Decision

Abdul Rasyid <abdulrasyid.fayufi@gmail.com> 12 April 2023 pukul 00.10
Kepada: Иванов Владимир Владимирович <vladimir.ivanov@aari.ru>

Dear Vladimir Ivanov
Editor of GES journal

We just want to know the progress of the manuscript entitled "CENDRAWASIH HOT POOL: STUDY OF THE HIGH-FREQUENCY OCCURRENCE OF HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA" after we sent the revised version of the manuscript.
Thank you.

Best regards,
Abd. Rasyid Jalil
(Corresponding Author)
[Kutipan teks disembunyikan]

Gmail **Abdul Rasyid <abdulrasyid.fayufi@gmail.com>**

GES Editor Decision

Иванов Владимир Владимирович <vladimir.ivanov@aari.ru> 12 April 2023 pukul 00.39
Kepada: abdulrasyid fayufi <abdulrasyid.fayufi@gmail.com>

Dear Dr Abd. Rasyid Jalil,

I have received the review on your revised manuscript several days days ago. You will get the decision in few days.

Kind regards,
Vladimir Ivanov

От: "abdulrasyid fayufi" <abdulrasyid.fayufi@gmail.com>
Кому: "Иванов Владимир Владимирович" <vladimir.ivanov@aari.ru>
Отправленные: Вторник, 11 Апрель 2023 г 19:10:37

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Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

GES Editor Decision

3 pesan

Dr. Vladimir V. Ivanov <no-reply@subs.elpub.ru> 15 April 2023 pukul 01.37
Balas Ke: "Dr. Vladimir V. Ivanov" <vladimir.ivanov@aari.ru>
Kepada: "Abd. Rasyid Jalil" <abdulrasyid.fayufi@gmail.com>

Dear Abd. Rasyid Jalil:

We have reached a decision regarding your submission to GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY, "CENDRAWASIH HOT POOL: STUDY OF THE HIGH-FREQUENCY OCCURRENCE OF HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA".

Our decision is to: accept your manuscript for publication. Congratulations and thank you very much for sending the results of your best researh to GES journal!

Dr. Vladimir V. Ivanov
AARI, MSU
vladimir.ivanov@aari.ru

Editorial Office

http://ges.rgo.ru/

Отказаться от рассылки

Dr. Vladimir V. Ivanov <no-reply@subs.elpub.ru> 15 April 2023 pukul 01.38
Balas Ke: "Dr. Vladimir V. Ivanov" <vladimir.ivanov@aari.ru>
Kepada: "Abd. Rasyid Jalil" <abdulrasyid.fayufi@gmail.com>

Dear Abd. Rasyid Jalil:

We have reached a decision regarding your submission to GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY, "CENDRAWASIH HOT POOL: STUDY OF THE HIGH-FREQUENCY OCCURRENCE OF HIGH SST PHENOMENA AT CENDRAWASIH BAY, PAPUA".

Our decision is to:

Dr. Vladimir V. Ivanov
AARI, MSU
vladimir.ivanov@aari.ru

[Kutipan teks disembunyikan]

Abdul Rasyid <abdulrasyid.fayufi@gmail.com> 27 April 2023 pukul 00.56
Kepada: "Dr. Vladimir V. Ivanov" <vladimir.ivanov@aari.ru>

Dear GES editor

Thank you very much for accepting our paper for publishing in your journal. We are waiting for the next process.

Best regards,
Abd. Rasyid Jalil
(Corresponding Author)
[Kutipan teks disembunyikan]

Gmail

Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

GES Editor Decision

4 pesan

GES Journal <ges-journal@geogr.msu.ru> 25 April 2023 pukul 15.07
Kepada: "abdulrasyid.fayufi@gmail.com" <abdulrasyid.fayufi@gmail.com>

Dear Dr. Abd. Rasyid Jalil,
We are pleased to announce that your manuscript has been approved for the Editorial Board consideration at the nearest meeting. Please, send us the final version of your manuscript without track changes along with the figures in high-resolution raster format (png or tiff) by the end of this week.

--
Best regards,
Nina Komova
Assistant editor
Geography, Environment, Sustainability
Editorial Office.
Website: http://ges.rgo.ru/jour

GES Journal <ges-journal@geogr.msu.ru> 2 Mei 2023 pukul 18.47
Kepada: "abdulrasyid.fayufi@gmail.com" <abdulrasyid.fayufi@gmail.com>
Cc: Abdul Malik <abdulmalik@unm.ac.id>, "aninosi@yahoo.co.id" <aninosi@yahoo.co.id>

Dear Dr. Abd. Rasyid Jalil,
Hope you are doing well. We asked you a few days ago about your manuscript files and haven't heard back. Please let us know if there's anything we can do to help.

--
Best regards,
Nina Komova
Assistant editor
Geography, Environment, Sustainability
Editorial Office.
Website: http://ges.rgo.ru/jour

25.04.2023, 10:07, "GES Journal" <ges-journal@geogr.msu.ru>:
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Abdul Rasyid <abdulrasyid.fayufi@gmail.com> 3 Mei 2023 pukul 01.28
Kepada: GES Journal <ges-journal@geogr.msu.ru>

Dear Nina Komova
Assistant Editor of GES

We apologize for the delay in sending the final version of manuscript (without track changes) and the figures in high resolution, because we just found your email in a spam folder.
Here is the final version of manuscript and the figures (attached)

Best regards,
Abd. Rasyid Jalil
(Corresponding Author)

[Kutipan teks disembunyikan]

--
Dr. Abd. Rasyid Jalil
Department of Marine Science
Faculty of Marine Science and Fisheries,
Universitas Hasanuddin,
Jl. Perintis Kemerdekaan Km. 10, Makassar, 90245 South Sulawesi, Indonesia

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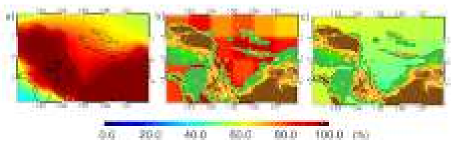

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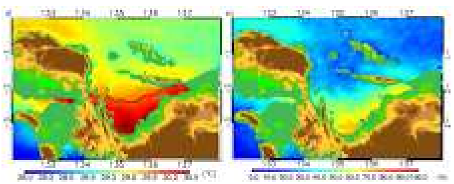

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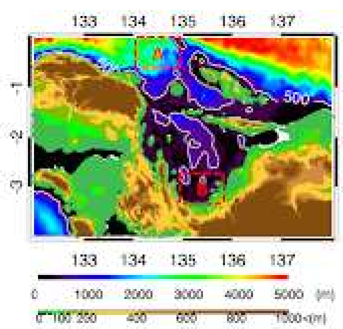

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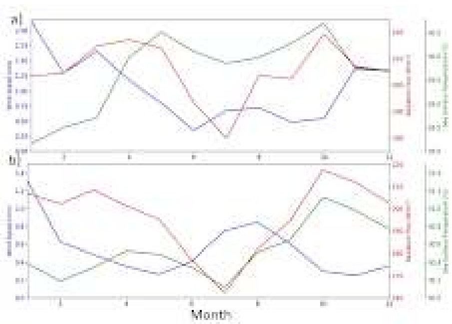

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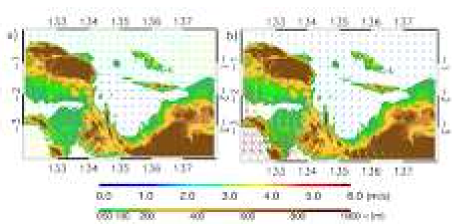

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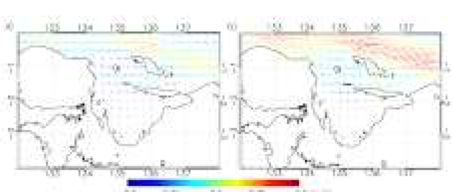

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Kepada: Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

Dear Dr. Abd. Rasyid Jalil,
Thank you for your files. Unfortunately, it is a common problem that emails end up in the spam folder.

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Best regards,
Nina Komova
Assistant editor
Geography, Environment, Sustainability
Editorial Office.
Website: http://ges.rgo.ru/jour

02.05.2023, 20:29, "Abdul Rasyid" <abdulrasyid.fayufi@gmail.com>:
[Kutipan teks disembunyikan]

Abd. Rasyid Jalil[1*], Anindya Wirasatriya[2,3], Fatwa Ramdani[4,5], Abdul Malik[6], Puji Rahmadi[7], Gentio Harsono[8], Riza Yuliratno Setiawan[9]

[1]Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Indonesia
[3]Coastal and Ocean Remote Sensing Laboratory, Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University, Indonesia
[4]Department of International Public Policy, Faculty of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[5]Program in Economic and Public Policy, Graduate School of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[6]Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Indonesia
[7]Research Center for Oceanography, Indonesian Institute of Science, Jakarta, Indonesia
[8]Faculty of Defense Technology Republic Indonesia, Indonesia Defense University, Jakarta, Indonesia
[9]Department of Fisheries, Gadjah Mada University, Yogyakarta, Indonesia.

***Corresponding author:** Abd. Rasyid Jalil, E-mail: abdulrasyid.fayufi@gmail.com

CENDERAWASIH HOT POOL: THE FREQUENT HIGH SST PHENOMENA AT CENDERAWASIH BAY, PAPUA

ABSTRACT. The warm pool has been used to define a water body with the characteristic of SST exceeding 28°C within a particular area and a relatively long period in an annual circle. However, there are regions with an annual mean SST measured above 30°C, and we classified them as Hot Pools because of the conditions of intense solar radiation and low wind speed. One of the Hot Pool spots was found in Indonesia, in Cenderawasih Bay. The present study examines the existence of the Cenderawasih Hot Pool using long-term observation of satellite SST data. We also used surface wind data, surface heat flux, and surface current to investigate their mechanisms. The results show that within 13 years of observation (2013-2015), SSTs in Cenderawasih Bay can reach more than 30°C with 50% occurrence within the observation period. Heat input comes from strong solar radiation, i.e., 50% of solar radiation is more than 200 W/m^2. The location is also dominated by low wind speed, i.e., 80% wind speed of lower than 4 m/s, which caused the low latent loss in Cenderawasih Bay. Cenderawasih Bay is fully isolated for surface currents during the dry and wet seasons since the easterly subsurface water flow does not enter the bay. The absence of strong currents prevents the mixing process, maintaining the high temperature in the surface layer. Those processes are figured out and become strong evidence to justify Cenderawasih Bay as one of the Hot Pool areas within the Indonesian seas.

KEYWORDS: Global climate; Sea Surface Temperature; Hot Pool Spot; Cenderawasih Bay.

INTRODUCTION

The western equatorial Pacific significantly influences the global climate. The warm pool, a region with average sea surface temperatures (SST) above 28°C, has a specific impact on the Earth's circulation (e.g., Wyrtki 1989; Yan et al. 1992; Clement and Seager 1999; Chongyin et al. 1999; Pierrehumbert 2000; Clement et al. 2005; Thoron et al. 2005; Herweijer et al. 2005).

On the other hand, high SST in tropical regions has attracted researchers to investigate the mechanisms since the formation of high SST requires a particular atmospheric process (e.g., Ramanathan and Collins 1991; Wallace 1992; Arking and Ziskin 1994). This process is depicted by Waliser and Graham (1993), which shows the relation between SSTs and deep convection. They utilized highly reflective cloud information from an arbitrary examination of monthly SST data with a grid spacing of 2° (produced from combined satellite observation and in situ data) and daily visible and infrared satellite image data. The highly reflective cloud increases along with the SST as it rises from 26°C to 29.5°C. In contrast, the highly reflective cloud diminishes with increased SST in the temperature from 29.5°C to 32°C. As a result, the analysis proved that several atmospheric processes impacted SSTs below and above 29.5°C.

By taking advantage of high temporal and spatial resolution SST products derived from satellite observations (i.e., daily and ≤ 25 km×25 km), several studies (Kawamura et al. 2008; Qin et al. 2007, 2008; Qin and Kawamura 2009, 2010; Wirasatriya et al. 2015, 2016, 2017a, 2020) were able to identify high SST events (i.e., more than 30°C) in specific areas and at certain periods and define them as Hot Event (HE). In summary, they concluded that considerable daily heat gains characterize the production of HE under high solar radiation and low wind speed brought on by "remote convection" mechanisms.

Wirasatriya et al. (2015) elaborated on the climatology of HEs in the western equatorial Pacific using the SST dataset derived from satellite microwave sensors. Throughout nine years of observation (2003-2011), they discovered 71 HE cases in the western equatorial Pacific, with the majority centered on the Solomon Islands and New Guinea Island's northern coasts, which extend eastward up to 160°W. According to the climatology, the region has solar radiation of more than 200 W/m^2 and wind speeds of less than 4 m/s. Low wind speeds heavily influence the mechanism for HE incidence in the western equatorial Pacific. Much of the equatorial region experiences sun radiation above 200 W/m2 during the HE periods. Low wind speeds minimize latent heat loss, which results in high SSTs and HEs in specific locations. Wirasatriya et al. (2015) also emphasized that high solar radiation and low wind speed are much more common during the development stage and less common during the decay stage. This study also demonstrated that a rise in the long-term mean SST in the western equatorial Pacific is correlated with an increase in the frequency of HE events. HEs were responsible for 51.5% of the SSTs >30°C in the warm pool region bounded by the 29.5 °C isotherms of the climatological SST. Thus, statistically, there is a relation between the occurrence of HE and the formation of the western Pacific warm pool. Moreover, Wirasatriya et al. (2020) demonstrated the role of HE in maintaining the warm mixed layer in the western Pacific warm pool. The frequent occurrence of HE transports heat from the surface layer to the deeper layer above the thermocline to maintain the warm mixed layer in the warm pool. Since the Pacific warm pool influences the global climate's variability through coupled ocean-atmosphere dynamics and thermodynamics (e.g., Clement and Seager 1999; Herweijer et al. 2005), this becomes an example of the contribution of high SST phenomena to regulate the global climate.

Within the Indonesian seas, the frequent appearance of high SST > 30°C has been reported by Tita et al. (2020) in Tomini Bay and by Swandiko et al. (2021) in the Malacca

Strait. Their appearances also the high solar radiation and weak wind. The morphology of the semi-enclosed waters causes the high-frequency occurrence of low wind speed by less than 4 m/s in both areas. Besides these two areas, there is no more study on the high SST phenomena within the Indonesian Seas.

The present study demonstrates the frequent high SST occurrence (more than 30°C) in Cenderawasih Bay. Cenderawasih Bay is in northern Papua Island, part of the western Pacific warm pool. It is semi-enclosed water with a deep basin, surrounded by mountain chains (Fig. 1). Cenderawasih Bay is the habitat for whale sharks (Ihsan et al. 2018). Since the area determines warm pool definition with SST climatology higher than 28°C, we call the high-frequency occurrence of SSTs higher than 30°C in the Cenderawasih Bay the Cenderawasih Hot Pool. Wirasatriya et al. (2015) found that the duration of HE occurrence in the western equatorial Pacific is no longer than two months since HE requires a typical condition of high solar radiation and low wind speed. Thus, it is interesting to understand the mechanisms of the high-frequency occurrence of high SST in the Cenderawasih Hot Pool.

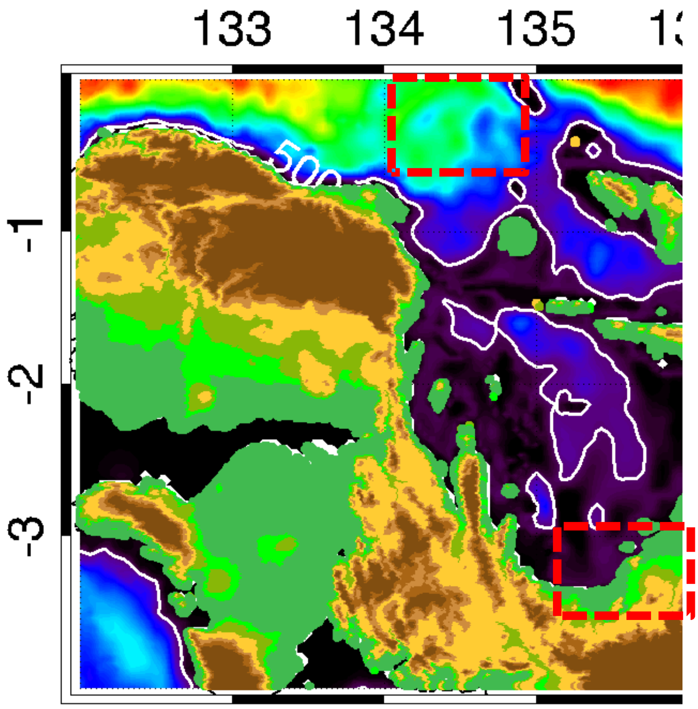

Fig. 1. Bathymetry and topography of Cenderawasih Bay. The dashed boxes A and B represent the sampling area for outside and inside Cenderawasih Bay, respectively, as shown in Fig. 5.

MATERIALS AND METHODS

We used the semi-daily 11 μm SST products from Moderate Resolution Imaging

Spectroradiometer (MODIS) Aqua Lv3 with a spatial resolution of 0.04°×0.04° (Esaias et al. 1998) and observation period from 2003 to 2015. The MODIS SST 11µthe Multi-Channel SST algorithm generates m by using brightness temperatures at 11 µm and 12 µm (Brown and Minnet 2009). The best accuracy was achieved by validating and testing this data against in-situ measurements (e.g., Lee et al. 2010; Qin et al. 2014; Ghanea et al. 2015).

We can obtain the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 from the following website: www.remss.com, and use it to calculate surface winds. As a result, CCMP is regarded as a Level-3 ocean vector wind analysis product. They are created utilizing data from moored buoys, satellites, and model winds. The surface wind data for spatial and temporal resolutions is 0.25°×0.25° respectively and quarter daily. This wind product has greater accuracy than other wind reanalysis data.

We used a 0.5° grid from the Objectively Analyzed Air-Sea Fluxes project to analyze daily latent heat fluxes and solar radiation (Yu and Weller, 2007). The period of observation for latent heat flux is from 2003 to 2015, but for solar radiation is only from 2003 to 2009 due to the availability of the data. Global 30 Arc-Second Elevation data was used to obtain topography. Global 30 Arc-Second Elevation (GTOPO30) data was used to obtain topography (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects). ETOPO, a one-arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry, provides bathymetry (https://www.ngdc.noaa.gov/mgg/global/). For oceanic parameters, we used the current reanalysis data from http://marine.copernicus.eu/ to obtain the seasonal variation of the current pattern at 100 m depth in the Cenderawasih Hot Pool.

To calculate the frequency occurrence of SST within 13 years of observation, we calculate the percentage of SST > 30°C occurrence in each grid. Since high SST of more than 30°C occurs during the condition of low wind speed (i.e., < 4 m/s) and high solar radiation (i.e., > 200 W/m^2) (Wirasatriya et al. 2015), we calculated the percentage of low wind speed and high solar radiation in the Cenderawasih Bay. Furthermore, we also calculated the percentage of low latent heat release (<120 W/m^2) to explain how wind speed influences the variability of SST. The equation for calculating the percentage is as follows:

(1)

where is percentage the percentage of high SST > 30°C or percentage of weak wind speed < 4 m/s or percentage of solar radiation > 200 W/m^2 or percentage of latent heat flux < 120W/m^2 at position (x,y); pi is the amount of SST data > 30°C or the amount of weak wind speed < 4 m/sec or the amount solar radiation > 200 W/m^2 or the amount of latent heat flux < 120W/m^2 at position (x,y). Furthermore, we also analyze the climatological mean of each parameter. To create monthly and monthly climatology, all geophysical parameters are incorporated as follows: (Wirasatriya et al. 2017b)

(2)

where is monthly mean value or monthly climatology value at position (x,y), is ith value of the data at (x,y) position and time t. Next, n is the number of data in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 13 data) for monthly calculation and monthly climatology calculation, respectively. Moreover, if pixel xi is a hollow pixel, it is not included in the calculation.

RESULTS AND DISCUSSION

Cenderawasih Hot Pool

The definition of the Cenderawasih Hot Pool is described in Fig. 2, which shows the climatological mean of SST and the percentage of daily SSTs more than 30°C from 2003 to 2015 (13 years). In Cenderawasih Bay, the mean SST at the southern part of 2°S is more than 30°C, and the high SSTs are more than 50%. It means that the mean SST in Cenderawasih Bay is higher than the definition of the western Pacific warm pool which is 28°C (Wyrtki 1989), and more than 3.5 years within 2003-2015, SSTs in Cenderawasih Bay can reach more than 30°C. At the southernmost of the bay, the mean SST reaches 30.5°C, with the percentage of high SSTs being more than 70%. It has become the hottest area of Cenderawasih Bay.

In contrast, in the area outside Cenderawasih Bay, i.e., the western Pacific warm pool's offshore seas, the percentage is less than 30%. Thus, this evidence supports the definition of Cenderawasih Bay as the Cenderawasih Hot Pool. The high-frequency occurrence of high SST in Cenderawasih Bay may correspond to whale sharks' yearly appearance. Ihsan et al. (2018) indicated the tolerance of whale sharks in high SST conditions.

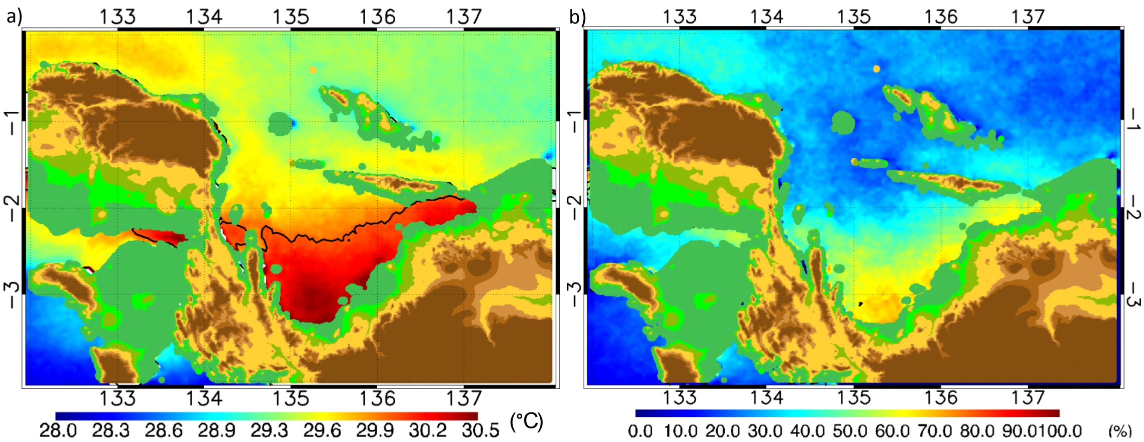

Fig. 2. Climatological mean of SST (a) and percentage of daily SSTs > 30°C during thirteen years of observation (2003-2015) (b). The black contour is 30°C.

Atmospheric Aspect of Cenderawasih Hot Pool

Fig. 3 clearly shows that low wind speed dominates Cenderawasih Bay, i.e., 80% wind speed < 4 m/s occurred during 2003-2015. This causes low latent loss in Cenderawasih Bay. For solar radiation, the percentage of high solar radiation inside and outside Cenderawasih Bay is almost similar i.e., nearly 50%, indicating that high solar radiation is not dominant in both areas. This means that, although high solar radiation does not frequently occur, the absence of strong wind speed may maintain the latent heat loss to keep the SST in Cenderawasih Bay higher than 30°C.

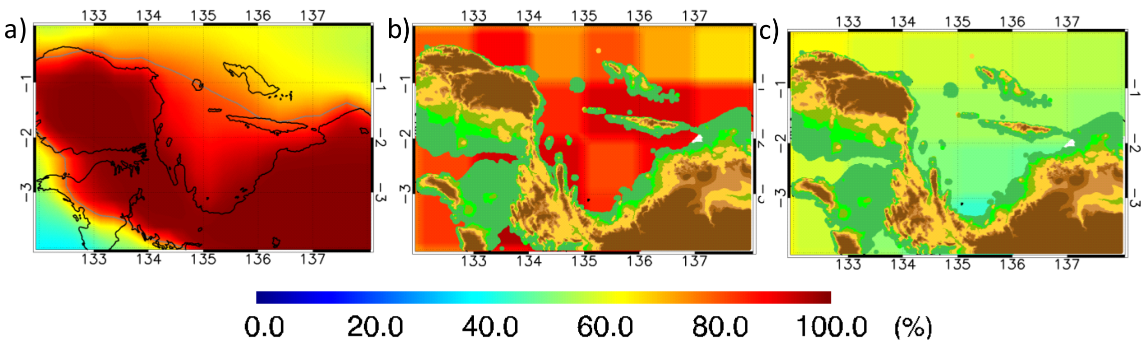

Fig. 3. The percentage of wind speed less than four m/s (a), latent heat release less than 120 W/m² (b), and solar radiation more than 200 W/m² (c).

To investigate how low wind speed occurs in the study area, we show the monthly climatology map of surface wind during summer and winter (Fig. 4). For both seasons, Cenderawasih Bay is protected from high wind speed due to high mountain chains in the western, southern, and eastern parts. In the northern part, small islands at the mouth of the bay prevent the strong wind speed from entering the bay. Thus, the role of topography is crucial for the occurrence of constant high SSTs in Cenderawasih Bay. The same tendencies are also found at the Tomini Bay and Malacca Strait, as indicated by Tita et al. (2020) and Swandiko et al. (2021).

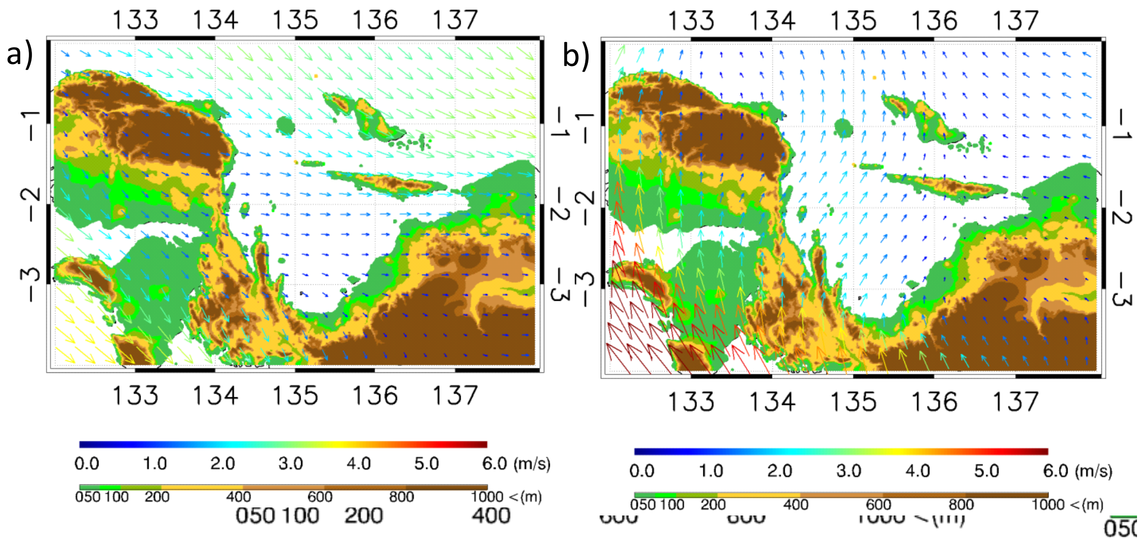

Fig. 4. Monthly climatology of surface wind speed during a) wet season (January) and b) dry season (August)

The influence of wind speed and solar radiation on the SST variation is further examined by plotting the monthly climatology of wind speed, solar radiation, and SST at areas A and B (Fig. 1), representing the areas outside and inside Cenderawasih Bay. Seasonal variations of SSTs are observed in both areas. The minimum SSTs occur during the wet and dry seasons, while the maximum SSTs during the transition season. This seasonal SST variability is similar to the other areas in the Indonesian seas, such as the Java Sea (Wirasatriya et al. 2018), Maluku Sea (Wirasatriya et al. 2019), Halmahera Sea (Setiawan et al. 2019), etc.

For the area outside Cenderawasih Bay, SST ranges from 28.2°C to 30.6°C. It is seen that the variability of SST is controlled by wind speed and solar radiation. From January to June, when wind speed decreases from 2.2 m/s to 0.3 m/s and solar radiation is more than 200 W/m², SST increases from 28.2°C to 30.5°C. From June to October, wind speed is lower than 1 m/s. In the absence of strong wind, the low SST in July is caused by the decrease of solar radiation to a minimum.

For the area inside Cenderawasih Bay, persistent high SST is observed as the SST ranges from 30.2°C to 31.1°C. It may be due to the low wind speed of fewer than 1 m/s for years. Thus, the variability of SST is seen as ruled by solar radiation. The minimum solar radiation causes the minimum SST in July. However, the absence of strong wind prevents latent heat loss that maintains the high SST inside Cenderawasih Bay.

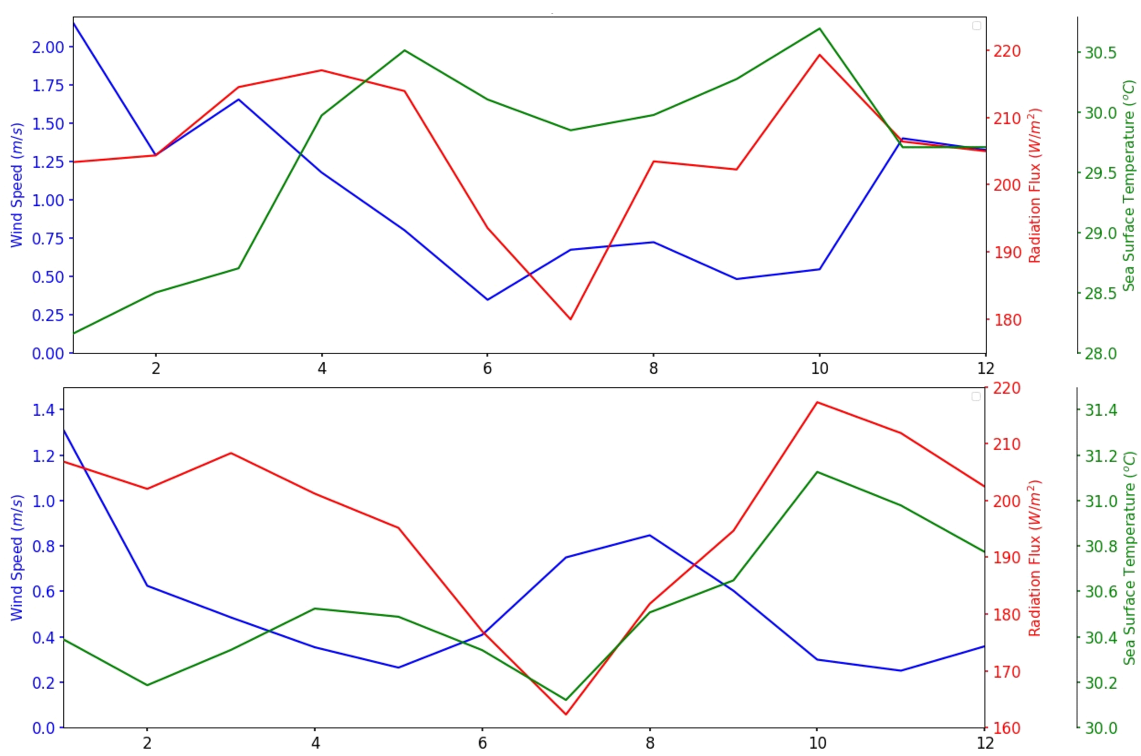

Fig. 5. Monthly climatology of SST, wind speed, and solar radiation at a) area outside and b) area inside Cenderawasih Bay, as shown in Fig. 1.

The oceanic aspect of Cenderawasih Hot Pool

To investigate the oceanic aspect of the Cenderawasih Hot Pool, we plotted the current patterns at 100 m depth shown in Fig. 6. A northwestward current has been identified north of Cenderawasih Bay. During the wet season (January), the speed of this current ranges from 0.5 m/s to 0.7 m/s. During the dry season (August), when the northwesterly wind disappears (Fig. 4b), the speed of the northwestward current increases. This northwestward current is known as the New Guinea Coastal Under Current (NGCUC). NGCUC is a permanent current feature at 200 m depth regardless of the wind reversals (Tsuchiya et al. 1989). Inside Cenderawasih Bay, strong currents are absent in this area, preventing the mixing process from maintaining the high temperature in the surface layer. During the dry and wet seasons, Cenderawasih Bay is fully isolated since the westward subsurface water flow does not enter Cenderawasih Bay. Thus, this isolated basin causes the Cenderawasih Bay area to be influenced mainly by the air-sea interaction process mentioned in the previous section creating Cenderawasih Hot Pool.

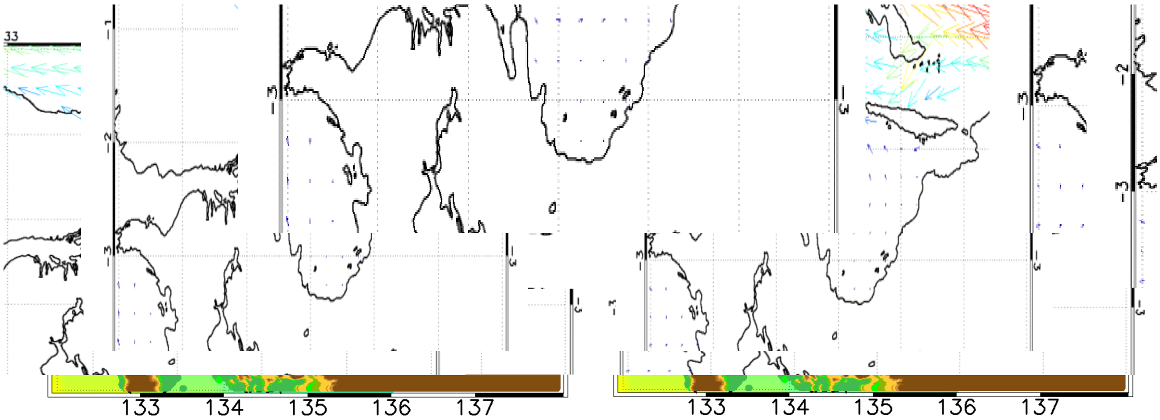

Fig. 6. Monthly climatology of current at 100 m depth in January (a) and August (b)

CONCLUSIONS

The hot Pool is used to categorize high SST episodes (>30^{0}C) in particular areas and during specific periods (relatively long periods). Since the "warm pool" has been used to define an area with the annual average SST distributed below 30^{0}C in dominant, therefore "hot pool" was taken to represent the area with SST dominated above 30^{0}C.

Under high solar radiation and low wind speed, this event is characterized by considerable daily heat gains. The constant high SST occurrence in Cenderawasih Bay, which is more than 50% of 13 years, SSTs can reach more than 30°C and are dominated by the condition of low wind speed, i.e., 80% wind speed is less than m/s along the years, also 50% solar radiation measured is more than 200 W/m^2. The current pattern at 100 m depth also shows that NGCUC does not enter Cenderawasih Bay. Thus, this indicates that Cenderawasih Bay is an isolated water. Those are the solid evidence for defining Cenderawasih Bay as the "Cenderawasih Hot Pool."

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CENDERAWASIH HOT POOL: THE FREQUENT HIGH SEA SURFACE TEMPERATURE PHENOMENA AT CENDERAWASIH BAY, PAPUA

Abd. Rasyid Jalil[1*], Anindya Wirasatriya[2,3], Fatwa Ramdani[4,5], Abdul Malik[6], Puji Rahmadi[7], Gentio Harsono[8], Riza Yuliratno Setiawan[9]

[1]Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Indonesia
[3]Coastal and Ocean Remote Sensing Laboratory, Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University, Indonesia
[4]Department of International Public Policy, Faculty of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[5]Program in Economic and Public Policy, Graduate School of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[6]Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Indonesia
[7]Research Center for Oceanography, Indonesian Institute of Science, Jakarta, Indonesia
[8]Faculty of Defense Technology Republic Indonesia, Indonesia Defense University, Jakarta, Indonesia
[9]Department of Fisheries, Gadjah Mada University, Yogyakarta, Indonesia.

***Corresponding author:** ~~Abd. Rasyid Jalil, E-mail:~~ abdulrasyid.fayufi@gmail.com

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ABSTRACT. The term "warm pool" ~~warm pool has been used~~refers to ~~define~~ a ~~water~~ body of water with the characteristic of SST exceeding 28°C within a particular area and a relatively long period in an annual circle. However, there are regions with an annual mean SST measured above 30°C, and we classified them as h~~H~~ot p~~P~~ools because of the conditions of intense solar radiation and low wind speed. One of the Hot Pool spots was found in Indonesia, in Cenderawasih Bay. The present study examines the existence of the Cenderawasih Hot Pool using long-term observation of satellite SST data. In order to learn more about their mechanisms, we also analyzed surface wind, surface heat flux, and surface current data. ~~We also used surface wind data, surface heat flux, and surface current to investigate their mechanisms.~~ The results show that ~~within 13 years of observation (2013-2015),~~ SSTs in Cenderawasih Bay ~~can reach more than 30°C with~~have a 50% chance of exceeding 30°C ~~occurrence within the observation period~~within the 13 years of study (2013-2015). ~~-~~Heat input comes from strong solar radiation, i.e., 50% of solar radiation is more than 200 W/m^2. The location is also dominated by low wind speed, i.e., 80% wind speed of lower than 4 m/s, which caused the low latent loss in Cenderawasih Bay. Cenderawasih Bay is fully ~~isolated for~~separated from surface currents during the dry and wet seasons since the easterly subsurface water flow does not enter the bay. The absence of strong currents prevents the mixing process, maintaining the high temperature in the

surface layer. Those processes are ~~figured out~~discovered and they serve as compelling ~~become strong~~ evidence to ~~justify~~ support Cenderawasih Bay as one of the Hot Pool areas within the Indonesian seas.

KEYWORDS: g~~G~~lobal climate; s~~S~~ea s~~S~~urface t~~T~~emperature; H~~H~~ot P~~P~~ool s~~S~~pot; Cenderawasih Bay~~.~~

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INTRODUCTION

The western equatorial Pacific has a big impact on ~~significantly influences~~ the ~~global~~ climate. The ~~warm pool, a region with average sea surface temperatures (SST) above 28°C, has a specific impact on the~~ Earth's circulation is specifically affected by the warm pool, an area with average sea surface temperatures (SST) exceeding 28°C (e.g., Wyrtki 1989; Yan et al. 1992; Clement and Seager 1999; Chongyin et al. 1999; Pierrehumbert 2000; Clement et al. 2005; Thoron et al. 2005; Herweijer et al. 2005).~~-~~

On the other hand, high SST in tropical regions has attracted researchers to investigate the mechanisms since the formation of high SST requires a particular atmospheric process (e.g., Ramanathan and Collins 1991; Wallace 1992; Arking and Ziskin 1994). This process is depicted by (Waliser and Graham ~~(~~1993), which shows the relation between SSTs and deep convection. ~~-~~They utilized highly reflective cloud information from an arbitrary examination of monthly SST data with a grid spacing of 2° ~~-~~(produced from combined satellite observation and in situ data) and daily visible and infrared satellite image data. The highly reflective cloud increases along with the SST as it rises from 26°C to 29.5°C. In contrast, the highly reflective cloud diminishes with increased SST in the temperature from 29.5°C to 32°C. As a result, the analysis proved that several atmospheric processes impacted SSTs below and above 29.5°C.

By taking advantage of high temporal and spatial resolution SST products derived from satellite observations (i.e., daily and ≤ 25 km×25 km), several studies (Kawamura et al. 2008; Qin et al. 2007, 2008; Qin and Kawamura 2009, 2010; Wirasatriya et al. 2015, 2016, 2017a, 2020) were able to identify high SST events (i.e., more than 30°C) in specific areas and at certain periods and define them as Hot Event (HE). In summary, they concluded that considerable daily heat gains characterize the production of HE under high solar radiation and low wind speed brought on by "remote convection" mechanisms.

(Wirasatriya et al. ~~(~~2015) elaborated on the climatology of HEs in the western equatorial Pacific using the SST dataset derived from satellite microwave sensors. Throughout nine years of observation (2003-2011), they discovered 71 HE cases in the western equatorial Pacific, with the majority centered on the Solomon Islands and New Guinea Island's northern coasts, which extend eastward up to 160°W. According to the climatology, the region has solar radiation of more than 200 W/m^2 and wind speeds of less than 4 m/s. Low wind speeds heavily influence the mechanism for HE incidence in the western equatorial Pacific. Much of the equatorial region experiences sun radiation above 200 W/m2 during the HE periods. Low wind speeds minimize latent heat loss, which results in high SSTs and HEs in specific locations. (Wirasatriya et al. ~~(~~2015) also emphasized that high solar radiation and low wind speed are much more common during the development stage and less common during the decay stage. This study also demonstrated that a rise in the long-term mean SST in the western equatorial Pacific is correlated with an increase in the frequency of HE events. HEs were responsible for 51.5% of the SSTs >30°C in the warm pool region bounded by the 29.5 °C isotherms of the climatological SST. Thus, statistically, there is a relation between the occurrence of HE and the formation of the western Pacific warm pool. Moreover, (Wirasatriya et al. (2020) demonstrated the role of HE in maintaining the warm mixed layer in the western Pacific warm pool. The frequent occurrence of HE transports heat from the surface layer to the deeper layer above the thermocline to maintain the warm mixed layer in the warm pool. Since the Pacific warm pool influences the global climate's variability through coupled ocean-atmosphere dynamics and thermodynamics (e.g., Clement and Seager 1999; Herweijer et al. 2005), this becomes an example of the contribution of high SST phenomena to regulate the global climate.

Within the Indonesian seas, the frequent appearance of high SST > 30°C has been reported by (Tita et al. (2020) in Tomini Bay and by (Swandiko et al. (2021) in the Malacca Strait. Their appearances also the high solar radiation and weak wind. The morphology of the semi-enclosed waters causes the high-frequency occurrence of low wind speed by less than 4 m/s in both areas. Besides these two areas, there is no more study on the high SST phenomena within the Indonesian Seas.

The present study demonstrates the frequent high SST occurrence (more than 30°C) in Cenderawasih Bay. Cenderawasih Bay is in northern Papua Island, part of the western Pacific warm pool. It is semi-enclosed water with a deep basin, surrounded by mountain chains (Fig. 1). Cenderawasih Bay is the habitat for whale sharks (Ihsan et al. 2018). Since the area determines warm pool definition with SST climatology higher than 28°C, we call the high-frequency occurrence of SSTs higher than 30°C in the Cenderawasih Bay the Cenderawasih Hot Pool. (Wirasatriya et al. (2015) found that the duration of HE occurrence in the western equatorial Pacific is no longer than two months since HE requires a typical condition of high solar radiation and low wind speed. Thus, it is interesting to understand the mechanisms of the high-frequency occurrence of high SST in the Cenderawasih Hot Pool.

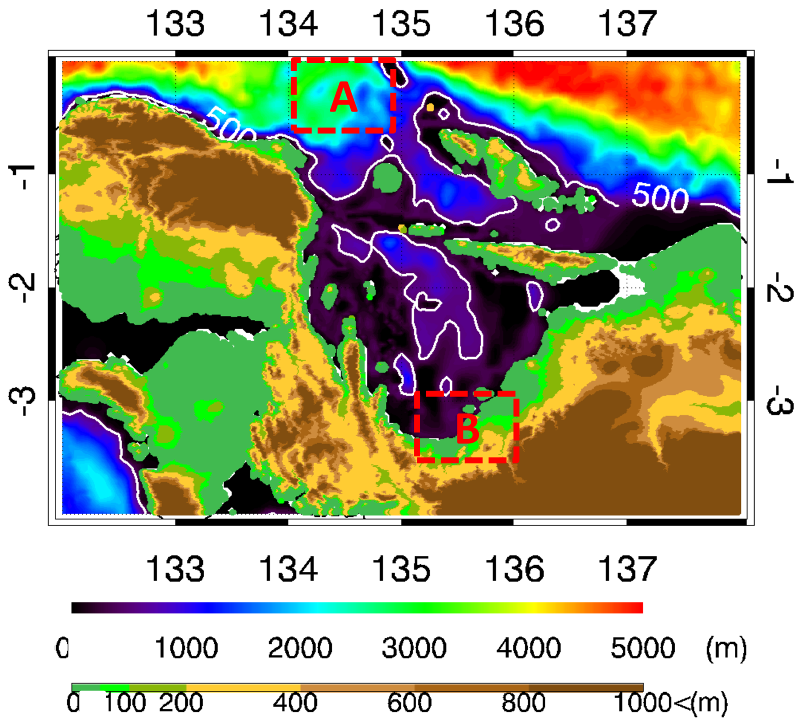

Fig. 1. Bathymetry and topography of Cenderawasih Bay. The dashed boxes A and B represent the sampling area for outside and inside Cenderawasih Bay, respectively, as shown in Fig. 5~~.~~

MATERIALS AND METHODS

We used the semi-daily 11 µm SST products from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua Lv3 with a spatial resolution of 0.04°×0.04° (Esaias et al. ~~–~~1998) and observation period from 2003 to 2015. The MODIS SST 11 µm the Multi-Channel SST algorithm generates m by using brightness temperatures at 11 µm and 12 µm (Brown and Minnet 2009). The best accuracy was achieved by validating and testing this data against in-situ measurements (e.g., Lee et al. 2010; Qin et al. 2014; Ghanea et al. 2015).

We can obtain the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 from the following website: ~~www.remss.com~~www.remss.com, and use it to calculate surface winds. As a result, CCMP is regarded as a Level-3 ocean vector wind analysis product. They are created utilizing data from moored buoys, satellites, and model winds. The surface wind data for spatial and temporal resolutions is 0.25°×0.25° respectively and quarter daily. This wind product has greater accuracy than other wind reanalysis data.

We used a 0.5° grid from the Objectively Analyzed Air-Sea Fluxes project to analyze daily latent heat fluxes and solar radiation (Yu and Weller~~,~~ 2007). The period of observation for latent heat flux is from 2003 to 2015, but for solar radiation is only from 2003 to 2009

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due to the availability of the data. Global 30 Arc-Second Elevation data was used to obtain topography. Global 30 Arc-Second Elevation (GTOPO30) data was used to obtain topography [1] . (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects). ETOPO, a one-arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry, provides bathymetry [2] . (https://www.ngdc.noaa.gov/mgg/global/). For oceanic parameters, we used the current reanalysis data from http://marine.copernicus.eu/http://marine.copernicus.eu/ to obtain the seasonal variation of the current pattern at 100 m depth in the Cenderawasih Hot Pool.

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To calculate the frequency occurrence of SST within 13 years of observation, we calculate the percentage of SST > 30°C occurrence in each grid. Since high SST of more than 30°C occurs during the condition of low wind speed (i.e., < 4 m/s) and high solar radiation (i.e., > 200 W/m^2) (Wirasatriya et al. 2015), we calculated the percentage of low wind speed and high solar radiation in the Cenderawasih Bay. Furthermore, we also calculated the percentage of low latent heat release (<120 W/m^2) to explain how wind speed influences the variability of SST. The equation for calculating the percentage is as follows:

$$\%(x, y) = \frac{1}{n}\sum_{i=1}^{n} pi\,(x, y) \times 100\% \qquad (1)$$

where $\%(x, y)$ is percentage the percentage of high SST > 30°C or percentage of weak wind speed < 4 m/s or percentage of solar radiation > 200 W/m^2 or percentage of latent heat flux < 120W/m^2 at position (x,y); pi is the amount of SST data > 30°C or the amount of weak wind speed < 4 m/sec or the amount solar radiation > 200 W/m^2 or the amount of latent heat flux < 120W/m^2 at position (x,y). Furthermore, we also analyze the climatological mean of each parameter. To create monthly and monthly climatology, all geophysical parameters are incorporated as follows: (Wirasatriya et al. 2017b):

$$\overline{X}(x, y) = \frac{1}{n}\sum_{i=1}^{n} xi\,(x, y, t) \qquad (2)$$

where $\overline{X}(x, y)$ is monthly mean value or monthly climatology value at position (x,y), $xi(x, y, t)$ is ith value of the data at (x,y) position and time t. Next, n is the number of data in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 13 data) for monthly calculation and monthly climatology calculation, respectively. Moreover, if pixel xi is a hollow pixel, it is not included in the calculation.

RESULTS AND DISCUSSION

Cenderawasih Hot Pool

The definition of the Cenderawasih Hot Pool is described in Fig. 2, which shows the climatological mean of SST and the percentage of daily SSTs more than 30°C from 2003 to 2015 (13 years). In Cenderawasih Bay, the mean SST at the southern part of 2°S is more than 30°C, and the high SSTs are more than 50%. It means that the mean SST in Cenderawasih Bay is higher than the definition of the western Pacific warm pool which is 28°C (Wyrtki 1989), and more than 3.5 years within 2003-2015, SSTs in Cenderawasih Bay can reach more than 30°C. At the southernmost of the bay, the mean SST reaches 30.5°C, with the percentage of high SSTs being more than 70%. It has become the hottest area of Cenderawasih Bay.

In contrast, in the area outside Cenderawasih Bay, i.e., the western Pacific warm pool's

[1] https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects

[2] https://www.ngdc.noaa.gov/mgg/global/

offshore seas, the percentage is less than 30%. Thus, this evidence supports the definition of Cenderawasih Bay as the Cenderawasih Hot Pool. The high-frequency occurrence of high SST in Cenderawasih Bay may correspond to whale sharks' yearly appearance. (Ihsan et al. (2018) indicated the tolerance of whale sharks in high SST conditions.

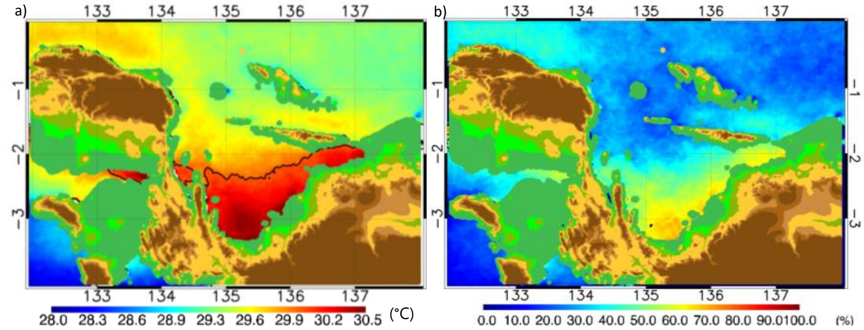

Fig. 2. Climatological mean of SST (a) and percentage of daily SSTs > 30°C during thirteen years of observation (2003-2015) (b). The black contour is 30°C.

Atmospheric Aspect of Cenderawasih Hot Pool

Fig. 3 clearly shows that low wind speed dominates Cenderawasih Bay, i.e., 80% wind speed < 4 m/s occurred during 2003-2015. This causes low latent loss in Cenderawasih Bay. For solar radiation, the percentage of high solar radiation inside and outside Cenderawasih Bay is almost similar i.e., nearly 50%, indicating that high solar radiation is not dominant in both areas. This means that, although high solar radiation does not frequently occur, the absence of strong wind speed may maintain the latent heat loss to keep the SST in Cenderawasih Bay higher than 30°C.

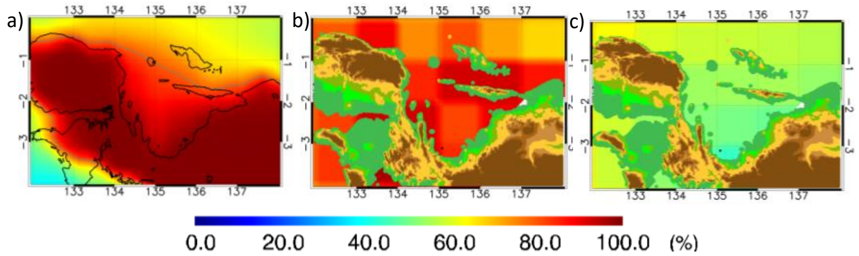

Fig. 3. The percentage of wind speed less than four m/s (a), latent heat release less than 120 W/m^2 (b), and solar radiation more than 200 W/m^2 (c).

To investigate how low wind speed occurs in the study area, we show the monthly climatology map of surface wind during summer and winter (Fig. 4). For both seasons, Cenderawasih Bay is protected from high wind speed due to high mountain chains in the western, southern, and eastern parts. In the northern part, small islands at the mouth of the bay prevent the strong wind speed from entering the bay. Thus, the role of topography is crucial for the occurrence of constant high SSTs in Cenderawasih Bay. The same tendencies are also found at the Tomini Bay and Malacca Strait, as indicated by (Tita et al. (2020) and (Swandiko et al. (2021).

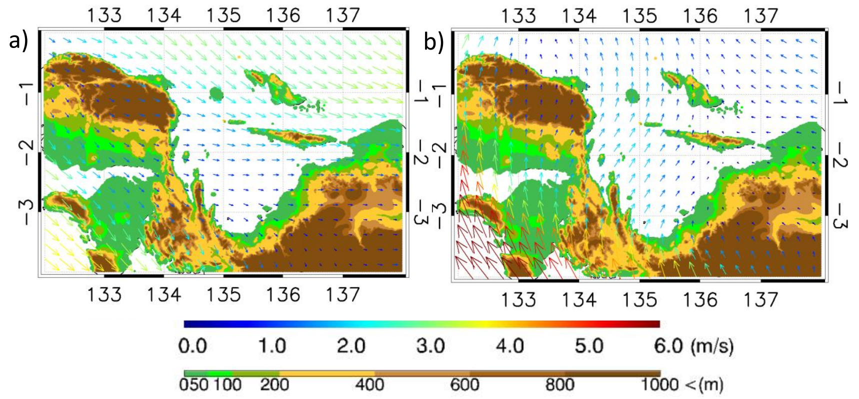

Fig. 4. Monthly climatology of surface wind speed during a) wet season (January) and b) dry season (August)

The influence of wind speed and solar radiation on the SST variation is further examined by plotting the monthly climatology of wind speed, solar radiation, and SST at areas A and B (Fig. 1), representing the areas outside and inside Cenderawasih Bay. –Seasonal variations of SSTs are observed in both areas. The minimum SSTs occur during the wet and dry seasons, while the maximum SSTs during the transition season. This seasonal SST variability is similar to the other areas in the Indonesian seas, such as the Java Sea (Wirasatriya et al. 2018), Maluku Sea (Wirasatriya et al. 2019), Halmahera Sea (Setiawan et al. 2019), etc.

For the area outside Cenderawasih Bay, SST ranges from 28.2°C to 30.6°C. It is seen that the variability of SST is controlled by wind speed and solar radiation. From January to

June, when wind speed decreases from 2.2 m/s to 0.3 m/s and solar radiation is more than 200 W/m^2, SST increases from 28.2°C to 30.5°C. From June to October, wind speed is lower than 1 m/s. In the absence of strong wind, the low SST in July is caused by the decrease of solar radiation to a minimum.

For the area inside Cenderawasih Bay, persistent high SST is observed as the SST ranges from 30.2°C to 31.1°C. It may be due to the low wind speed of fewer than 1 m/s for years. Thus, the variability of SST is seen as ruled by solar radiation. The minimum solar radiation causes the minimum SST in July. However, the absence of strong wind prevents latent heat loss that maintains the high SST inside Cenderawasih Bay.

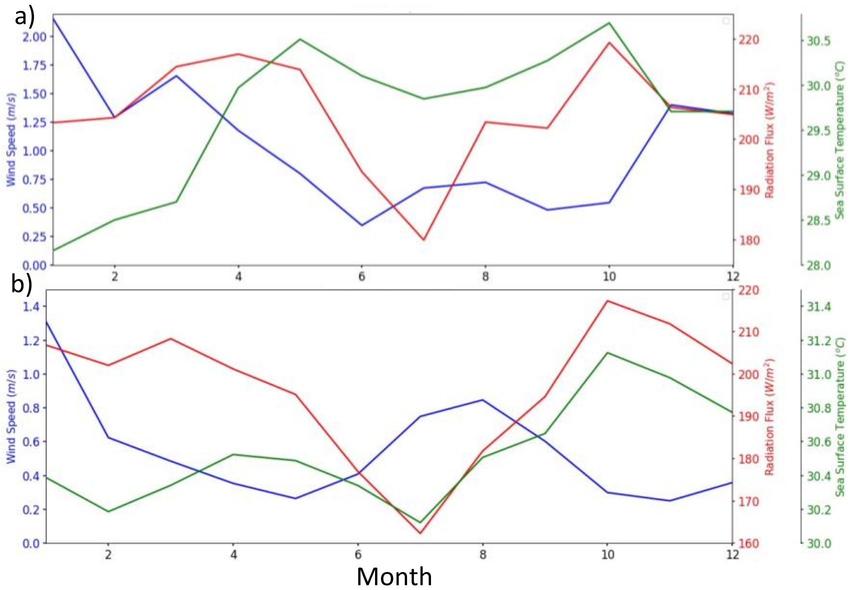

Fig. 5. Monthly climatology of SST, wind speed, and solar radiation at a) area outside and b) area inside Cenderawasih Bay, as shown in Fig. 1.

The oceanic aspect of Cenderawasih Hot Pool

To investigate the oceanic aspect of the Cenderawasih Hot Pool, we plotted the current patterns at 100 m depth shown in Fig. 6. A northwestward current has been identified north of Cenderawasih Bay. During the wet season (January), the speed of this current ranges from 0.5 m/s to 0.7 m/s. During the dry season (August), when the northwesterly wind disappears (Fig. 4b), the speed of the northwestward current increases. This northwestward current is known as the New Guinea Coastal Under Current (NGCUC). NGCUC is a permanent current feature at 200 m depth regardless of the wind reversals (Tsuchiya et al. 1989). Inside Cenderawasih Bay, strong currents are absent in this area, preventing the mixing process from maintaining the high temperature in the surface layer. During the dry and wet seasons, Cenderawasih Bay is fully isolated since the westward subsurface water flow does not enter Cenderawasih Bay. Thus, this isolated basin causes the Cenderawasih Bay area to be influenced mainly by the air-sea interaction process mentioned in the previous section creating Cenderawasih Hot Pool.

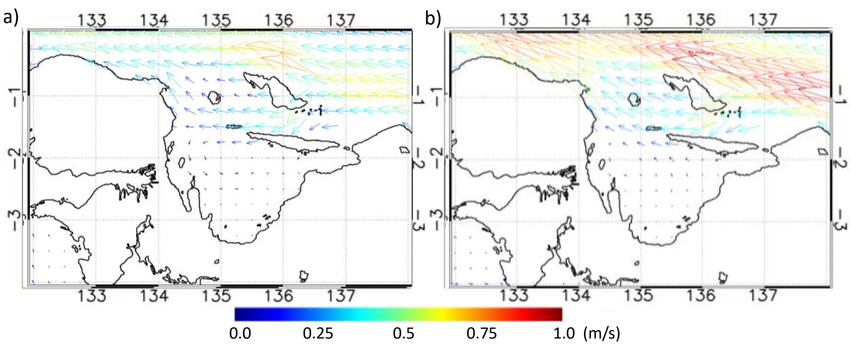

Fig. 6. Monthly climatology of current at 100 m depth in January (a) and August (b)

CONCLUSIONS

The hot Pool is used to categorize high SST episodes (>30°C) in particular areas and during specific periods (relatively long periods). Since the term "warm pool" has been used to define an area with the annual average SST distributed below 30°C in dominant, therefore "hot pool" was taken to represent the area with SST dominated above 30°C.

Under high solar radiation and low wind speed, this event is characterized by considerable daily heat gains. The constant high SST occurrence in Cenderawasih Bay, which is more than 50% of 13 years, SSTs can reach more than 30°C and are dominated by the condition of low wind speed, i.e., 80% wind speed is less than m/s along the years, also 50% solar radiation measured is more than 200 W/m^2. The current pattern at 100 m depth also shows that NGCUC does not enter Cenderawasih Bay. Thus, this indicates that Cenderawasih Bay is an isolated water. Those are the solid evidence for defining Cenderawasih Bay as the "Cenderawasih Hot Pool."

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Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

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Faculty of Marine Science and Fisheries,
Universitas Hasanuddin,
Jl. Perintis Kemerdekaan Km. 10, Makassar, 90245 South Sulawesi, Indonesia

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CENDERAWASIH HOT POOL: THE FREQUENT HIGH SEA SURFACE TEMPERATURE PHENOMENA AT CENDERAWASIH BAY, PAPUA

Abd. Rasyid Jalil[1*], Anindya Wirasatriya[2,3], Abdul Malik[4], Fatwa Ramdani[5,6], Puji Rahmadi[7], Gentio Harsono[8,9], Riza Yuliratno Setiawan[10]

[1]Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Indonesia
[3]Coastal and Ocean Remote Sensing Laboratory, Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University, Indonesia
[4]Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Indonesia
[5]Department of International Public Policy, Faculty of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[6]Program in Economic and Public Policy, Graduate School of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[7]Research Center for Oceanography, National Research and Innovation Agency, Jakarta, Indonesia
[8]Faculty of Science and Defense Technology, Republic Indonesia Defense University, Bogor, Indonesia
[9]Hydro-Oceanography Service Center, Indonesian Navy
[10]Department of Fisheries, Faculty of Agriculture, Gadjah Mada University, Yogyakarta, Indonesia.
***Corresponding author:** abdulrasyid.fayufi@gmail.com

ABSTRACT. The term "warm pool" refers to a body of water with the characteristic of SST exceeding 28°C within a particular area and a relatively long period in an annual circle. However, there are regions with an annual mean SST measured above 30°C, and we classified them as hot pools because of the conditions of intense solar radiation and low wind speed. One of the Hot Pool spots was found in Indonesia, in Cenderawasih Bay. The present study examines the existence of the Cenderawasih Hot Pool using long-term observation of satellite SST data. In order to learn more about their mechanisms, we also analyzed surface wind, surface heat flux, and surface current data. The results show that SSTs in Cenderawasih Bay have a 50% chance of exceeding 30°C within the 13 years of study (2013-2015). Heat input comes from strong solar radiation, i.e., 50% of solar radiation is more than 200 W/m^2. The location is also dominated by low wind speed, i.e., 80% wind speed of lower than 4 m/s, which caused the low latent loss in Cenderawasih Bay. Cenderawasih Bay is fully separated from surface currents during the dry and wet seasons since the easterly subsurface water flow does not enter the bay. The absence of strong currents prevents the mixing process, maintaining the high temperature in the surface layer. Those processes are discovered and they serve as compelling evidence to support Cenderawasih Bay as one of the Hot Pool areas within the Indonesian seas.

KEYWORDS: global climate; sea surface temperature; Hot Pool spot; Cenderawasih Bay

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INTRODUCTION

The western equatorial Pacific has a big impact on the climate. The Earth's circulation is specifically affected by the warm pool, an area with average sea surface temperatures (SST) exceeding 28°C (e.g., Wyrtki 1989; Yan et al. 1992; Clement and Seager 1999; Chongyin et al. 1999; Pierrehumbert 2000; Clement et al. 2005; Thoron et al. 2005; Herweijer et al. 2005).

On the other hand, high SST in tropical regions has attracted researchers to investigate the mechanisms since the formation of high SST requires a particular atmospheric process (e.g., Ramanathan and Collins 1991; Wallace 1992; Arking and Ziskin 1994). This process is depicted by (Waliser and Graham 1993), which shows the relation between SSTs and deep convection. They utilized highly reflective cloud information from an arbitrary examination of monthly SST data with a grid spacing of 2° (produced from combined satellite observation and in situ data) and daily visible and infrared satellite image data. The highly reflective cloud increases along with the SST as it rises from 26°C to 29.5°C. In contrast, the highly reflective cloud diminishes with increased SST in the temperature from 29.5°C to 32°C. As a result, the analysis proved that several atmospheric processes impacted SSTs below and above 29.5°C.

By taking advantage of high temporal and spatial resolution SST products derived from satellite observations (i.e., daily and ≤ 25 km×25 km), several studies (Kawamura et al. 2008; Qin et al. 2007, 2008; Qin and Kawamura 2009, 2010; Wirasatriya et al. 2015, 2016, 2017a, 2020) were able to identify high SST events (i.e., more than 30°C) in specific areas and at certain periods and define them as Hot Event (HE). In summary, they concluded that considerable daily heat gains characterize the production of HE under high solar radiation and low wind speed brought on by "remote convection" mechanisms.

(Wirasatriya et al. 2015) elaborated on the climatology of HEs in the western equatorial Pacific using the SST dataset derived from satellite microwave sensors. Throughout nine years of observation (2003-2011), they discovered 71 HE cases in the western equatorial Pacific, with the majority centered on the Solomon Islands and New Guinea Island's northern coasts, which extend eastward up to 160°W. According to the climatology, the region has solar radiation of more than 200 W/m^2 and wind speeds of less than 4 m/s. Low wind speeds heavily influence the mechanism for HE incidence in the western equatorial Pacific. Much of the equatorial region experiences sun radiation above 200 W/m2 during the HE periods. Low wind speeds minimize latent heat loss, which results in high SSTs and HEs in specific locations. (Wirasatriya et al. 2015) also emphasized that high solar radiation and low wind speed are much more common during the development stage and less common during the decay stage. This study also demonstrated that a rise in the long-term mean SST in the western equatorial Pacific is correlated with an increase in the frequency of HE events. HEs were responsible for 51.5% of the SSTs >30°C in the warm pool region bounded by the 29.5 °C isotherms of the climatological SST. Thus, statistically, there is a relation between the occurrence of HE and the formation of the western Pacific warm pool. Moreover, (Wirasatriya et al. 2020) demonstrated the role of HE in maintaining the warm mixed layer in the western Pacific warm pool. The frequent occurrence of HE transports heat from the surface layer to the deeper layer above the thermocline to maintain the warm mixed layer in the warm pool. Since the Pacific warm pool influences the global climate's variability through coupled ocean-atmosphere dynamics and thermodynamics (e.g., Clement and Seager 1999; Herweijer et al. 2005), this becomes an example of the contribution of high SST phenomena to regulate the global climate.

Within the Indonesian seas, the frequent appearance of high SST > 30°C has been reported by (Tita et al. 2020) in Tomini Bay and by (Swandiko et al. 2021) in the Malacca Strait. Their appearances also the high solar radiation and weak wind. The morphology of the semi-enclosed waters causes the high-frequency occurrence of low wind speed by less than 4 m/s in both areas. Besides these two areas, there is no more study on the high SST phenomena within the Indonesian Seas.

The present study demonstrates the frequent high SST occurrence (more than 30°C) in Cenderawasih Bay. Cenderawasih Bay is in northern Papua Island, part of the western Pacific warm pool. It is semi-enclosed water with a deep basin, surrounded by mountain chains (Fig. 1). Cenderawasih Bay is the habitat for whale sharks (Ihsan et al. 2018). Since the area determines warm pool definition with SST climatology higher than 28°C, we call the high-frequency occurrence of SSTs higher than 30°C in the Cenderawasih Bay the Cenderawasih Hot Pool. (Wirasatriya et al. 2015) found that the duration of HE occurrence in the western equatorial Pacific is no longer than two months since HE requires a typical condition of high solar radiation and low wind speed. Thus, it is interesting to understand the mechanisms of the high-frequency occurrence of high SST in the Cenderawasih Hot Pool.

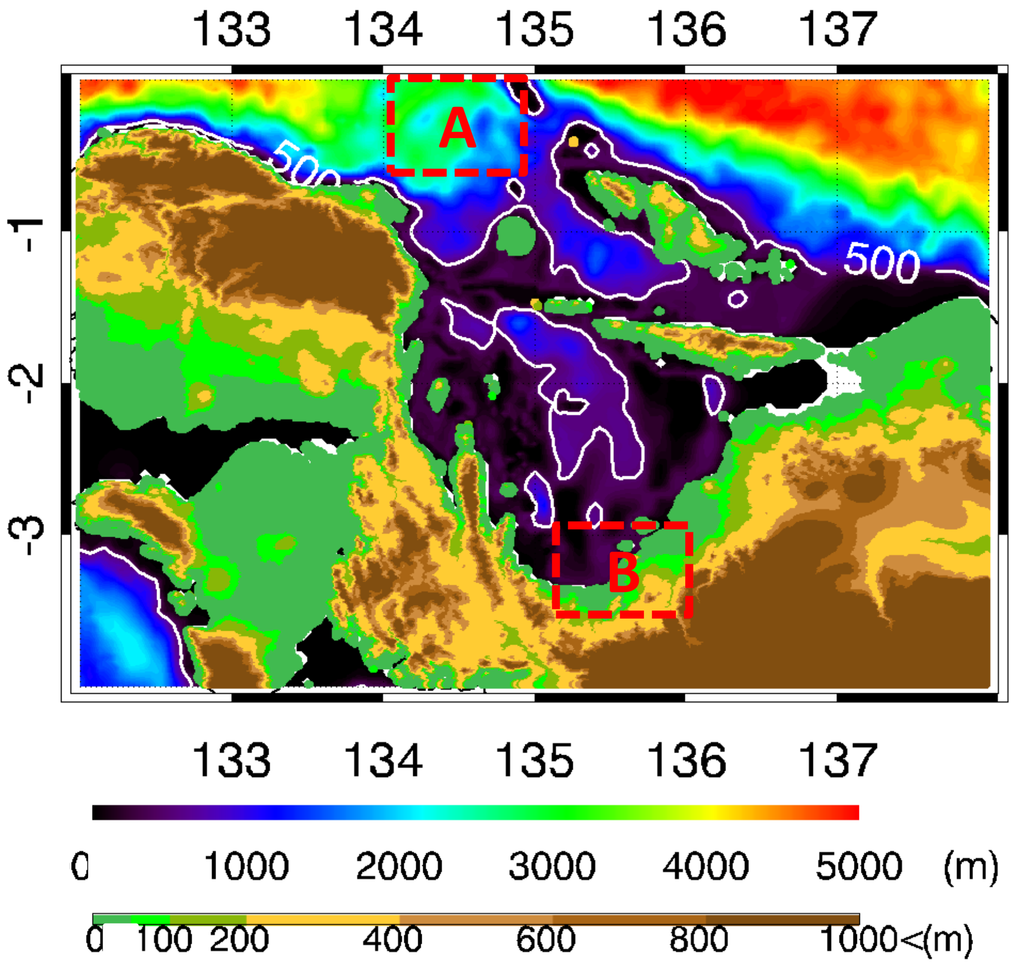

Fig. 1. Bathymetry and topography of Cenderawasih Bay. The dashed boxes A and B represent the sampling area for outside and inside Cenderawasih Bay,

respectively, as shown in Fig. 5

MATERIALS AND METHODS

We used the semi-daily 11 µm SST products from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua Lv3 with a spatial resolution of 0.04°×0.04° (Esaias et al. 1998) and observation period from 2003 to 2015. The MODIS SST 11 µm the Multi-Channel SST algorithm generates m by using brightness temperatures at 11 µm and 12 µm (Brown and Minnet 2009). The best accuracy was achieved by validating and testing this data against in-situ measurements (e.g., Lee et al. 2010; Qin et al. 2014; Ghanea et al. 2015).

We can obtain the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 from the following website: www.remss.com, and use it to calculate surface winds. As a result, CCMP is regarded as a Level-3 ocean vector wind analysis product. They are created utilizing data from moored buoys, satellites, and model winds. The surface wind data for spatial and temporal resolutions is 0.25°×0.25° respectively and quarter daily. This wind product has greater accuracy than other wind reanalysis data.

We used a 0.5° grid from the Objectively Analyzed Air-Sea Fluxes project to analyze daily latent heat fluxes and solar radiation (Yu and Weller 2007). The period of observation for latent heat flux is from 2003 to 2015, but for solar radiation is only from 2003 to 2009 due to the availability of the data. Global 30 Arc-Second Elevation data was used to obtain topography. Global 30 Arc-Second Elevation (GTOPO30) data was used to obtain topography[1]. ETOPO, a one-arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry, provides bathymetry[2]. For oceanic parameters, we used the current reanalysis data from http://marine.copernicus.eu/ to obtain the seasonal variation of the current pattern at 100 m depth in the Cenderawasih Hot Pool.

To calculate the frequency occurrence of SST within 13 years of observation, we calculate the percentage of SST > 30°C occurrence in each grid. Since high SST of more than 30°C occurs during the condition of low wind speed (i.e., < 4 m/s) and high solar radiation (i.e., > 200 W/m^2) (Wirasatriya et al. 2015), we calculated the percentage of low wind speed and high solar radiation in the Cenderawasih Bay. Furthermore, we also calculated the percentage of low latent heat release (<120 W/m^2) to explain how wind speed influences the variability of SST. The equation for calculating the percentage is as follows:

$$\%(x, y) = \frac{1}{n}\sum_{i=1}^{n} pi\,(x, y) \times 100\% \qquad (1)$$

where $\%(x, y)$ is percentage the percentage of high SST > 30°C or percentage of weak wind speed < 4 m/s or percentage of solar radiation > 200 W/m^2 or percentage of latent heat flux < 120W/m^2 at position (x,y); pi is the amount of SST data > 30°C or the amount of weak wind speed < 4 m/sec or the amount solar radiation > 200 W/m^2 or the amount of latent heat flux < 120W/m^2 at position (x,y). Furthermore, we also analyze the climatological mean of each parameter. To create monthly and monthly climatology, all geophysical parameters are incorporated as follows (Wirasatriya et al. 2017b):

$$\overline{X}(x, y) = \frac{1}{n}\sum_{i=1}^{n} xi\,(x, y, t) \qquad (2)$$

where $\overline{X}(x, y)$ is monthly mean value or monthly climatology value at position (x,y), $xi(x, y, t)$ is ith value of the data at (x,y) position and time t. Next, n is the number of data

[1] https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects

[2] https://www.ngdc.noaa.gov/mgg/global/

in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 13 data) for monthly calculation and monthly climatology calculation, respectively. Moreover, if pixel xi is a hollow pixel, it is not included in the calculation.

RESULTS AND DISCUSSION

Cenderawasih Hot Pool

The definition of the Cenderawasih Hot Pool is described in Fig. 2, which shows the climatological mean of SST and the percentage of daily SSTs more than 30°C from 2003 to 2015 (13 years). In Cenderawasih Bay, the mean SST at the southern part of 2°S is more than 30°C, and the high SSTs are more than 50%. It means that the mean SST in Cenderawasih Bay is higher than the definition of the western Pacific warm pool which is 28°C (Wyrtki 1989), and more than 3.5 years within 2003-2015, SSTs in Cenderawasih Bay can reach more than 30°C. At the southernmost of the bay, the mean SST reaches 30.5°C, with the percentage of high SSTs being more than 70%. It has become the hottest area of Cenderawasih Bay.

In contrast, in the area outside Cenderawasih Bay, i.e., the western Pacific warm pool's offshore seas, the percentage is less than 30%. Thus, this evidence supports the definition of Cenderawasih Bay as the Cenderawasih Hot Pool. The high-frequency occurrence of high SST in Cenderawasih Bay may correspond to whale sharks' yearly appearance. (Ihsan et al. 2018) indicated the tolerance of whale sharks in high SST conditions.

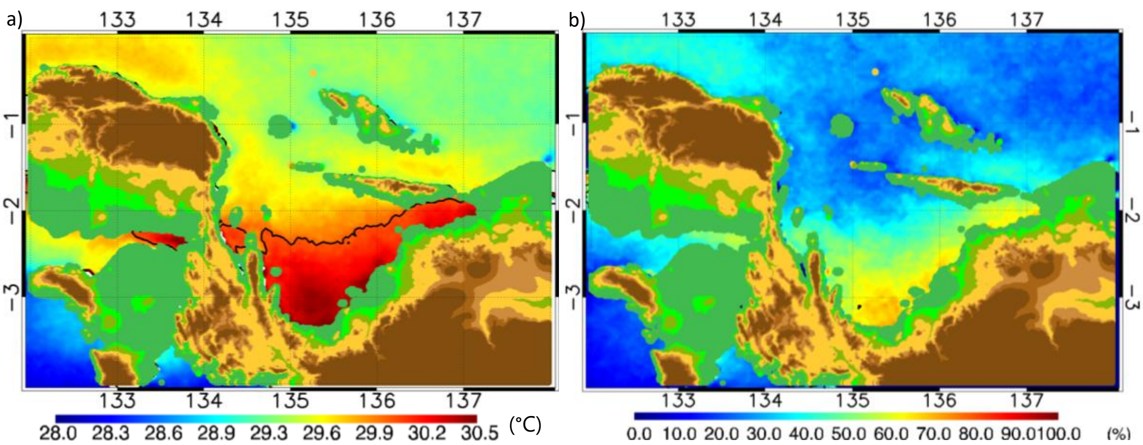

Fig. 2. Climatological mean of SST (a) and percentage of daily SSTs > 30°C during thirteen years of observation (2003-2015) (b). The black contour is 30°C

Atmospheric Aspect of Cenderawasih Hot Pool

Fig. 3 clearly shows that low wind speed dominates Cenderawasih Bay, i.e., 80% wind speed < 4 m/s occurred during 2003-2015. This causes low latent loss in Cenderawasih Bay. For solar radiation, the percentage of high solar radiation inside and outside Cenderawasih Bay is almost similar i.e., nearly 50%, indicating that high solar radiation is not dominant in both areas. This means that, although high solar radiation does not frequently occur, the absence of strong wind speed may maintain the latent heat loss to keep the SST in Cenderawasih Bay higher than 30°C.

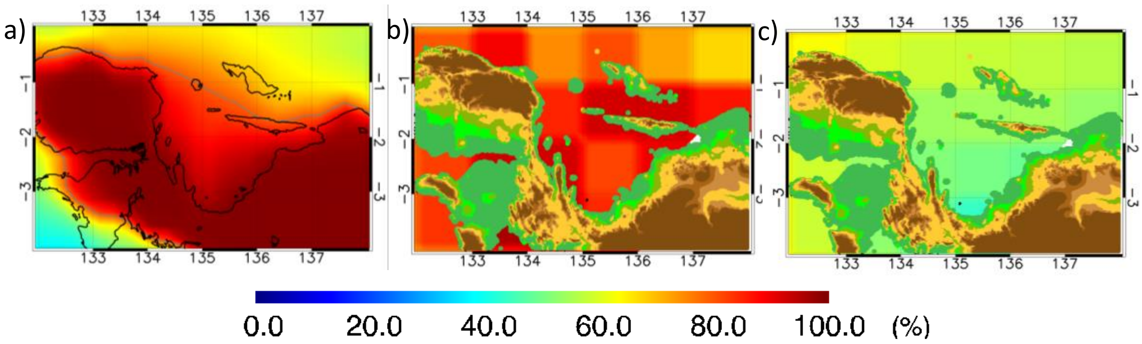

Fig. 3. The percentage of wind speed less than four m/s (a), latent heat release less than 120 W/m^2 (b), and solar radiation more than 200 W/m^2 (c)

To investigate how low wind speed occurs in the study area, we show the monthly climatology map of surface wind during summer and winter (Fig. 4). For both seasons, Cenderawasih Bay is protected from high wind speed due to high mountain chains in the western, southern, and eastern parts. In the northern part, small islands at the mouth of the bay prevent the strong wind speed from entering the bay. Thus, the role of topography is crucial for the occurrence of constant high SSTs in Cenderawasih Bay. The same tendencies are also found at the Tomini Bay and Malacca Strait, as indicated by (Tita et al. 2020) and (Swandiko et al. 2021).

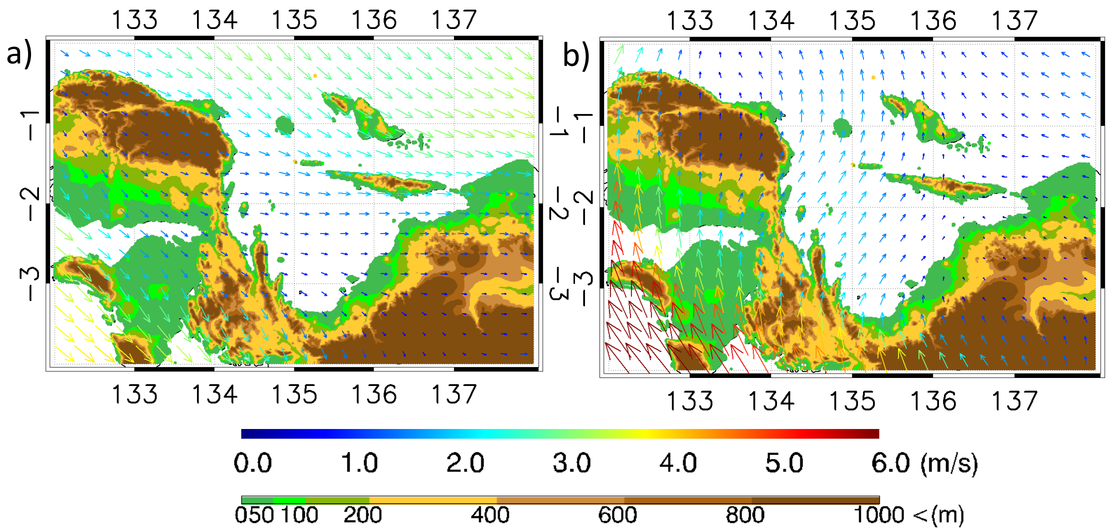

Fig. 4. Monthly climatology of surface wind speed during a) wet season (January) and b) dry season (August)

The influence of wind speed and solar radiation on the SST variation is further examined by plotting the monthly climatology of wind speed, solar radiation, and SST at areas A and B (Fig. 1), representing the areas outside and inside Cenderawasih Bay. Seasonal variations of SSTs are observed in both areas. The minimum SSTs occur during the wet and dry seasons, while the maximum SSTs during the transition season. This seasonal SST variability is similar to the other areas in the Indonesian seas, such as the Java Sea (Wirasatriya et al. 2018), Maluku Sea (Wirasatriya et al. 2019), Halmahera Sea (Setiawan et al. 2019), etc.

For the area outside Cenderawasih Bay, SST ranges from 28.2°C to 30.6°C. It is seen that the variability of SST is controlled by wind speed and solar radiation. From January to

June, when wind speed decreases from 2.2 m/s to 0.3 m/s and solar radiation is more than 200 W/m^2, SST increases from 28.2°C to 30.5°C. From June to October, wind speed is lower than 1 m/s. In the absence of strong wind, the low SST in July is caused by the decrease of solar radiation to a minimum.

For the area inside Cenderawasih Bay, persistent high SST is observed as the SST ranges from 30.2°C to 31.1°C. It may be due to the low wind speed of fewer than 1 m/s for years. Thus, the variability of SST is seen as ruled by solar radiation. The minimum solar radiation causes the minimum SST in July. However, the absence of strong wind prevents latent heat loss that maintains the high SST inside Cenderawasih Bay.

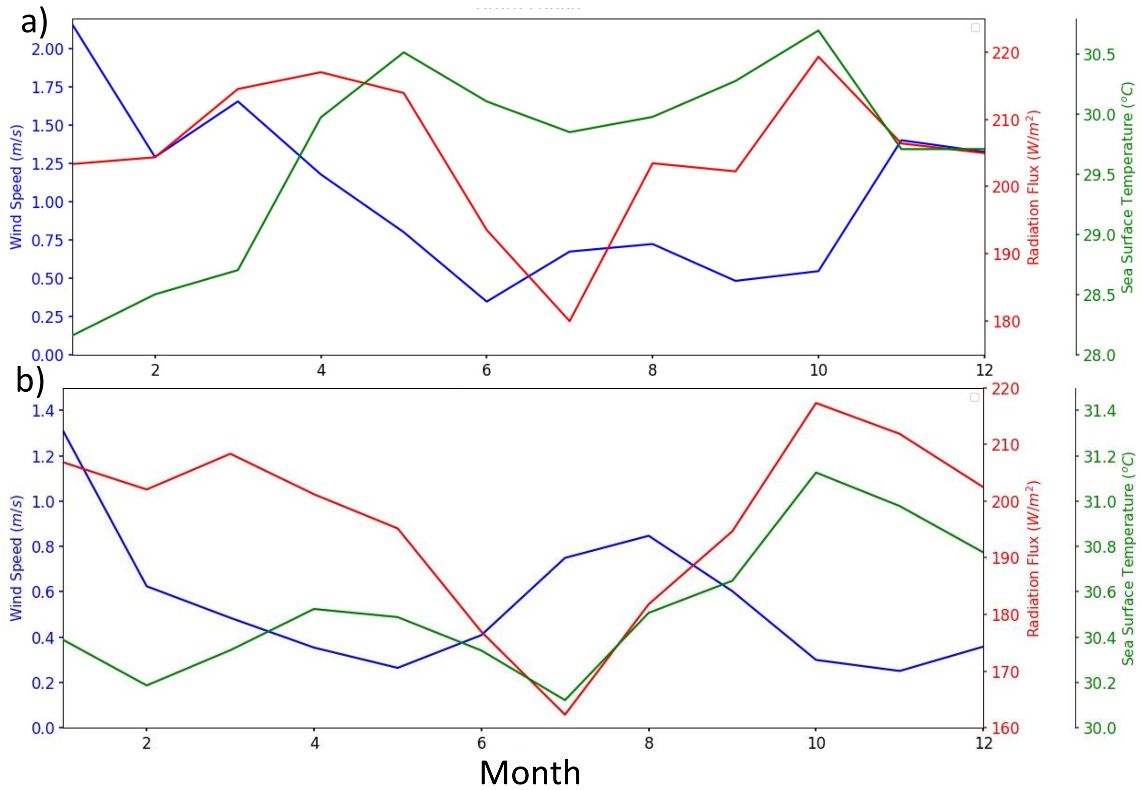

Fig. 5. Monthly climatology of SST, wind speed, and solar radiation at a) area outside and b) area inside Cenderawasih Bay, as shown in Fig. 1

The oceanic aspect of Cenderawasih Hot Pool

To investigate the oceanic aspect of the Cenderawasih Hot Pool, we plotted the current patterns at 100 m depth shown in Fig. 6. A northwestward current has been identified north of Cenderawasih Bay. During the wet season (January), the speed of this current ranges from 0.5 m/s to 0.7 m/s. During the dry season (August), when the northwesterly wind disappears (Fig. 4b), the speed of the northwestward current increases. This northwestward current is known as the New Guinea Coastal Under Current (NGCUC). NGCUC is a permanent current feature at 200 m depth regardless of the wind reversals (Tsuchiya et al. 1989). Inside Cenderawasih Bay, strong currents are absent in this area, preventing the mixing process from maintaining the high temperature in the surface layer. During the dry and wet seasons, Cenderawasih Bay is fully isolated since the westward subsurface water flow does not enter Cenderawasih Bay. Thus, this isolated basin causes the Cenderawasih Bay area to be influenced mainly by the air-sea interaction process mentioned in the previous section creating Cenderawasih Hot Pool.

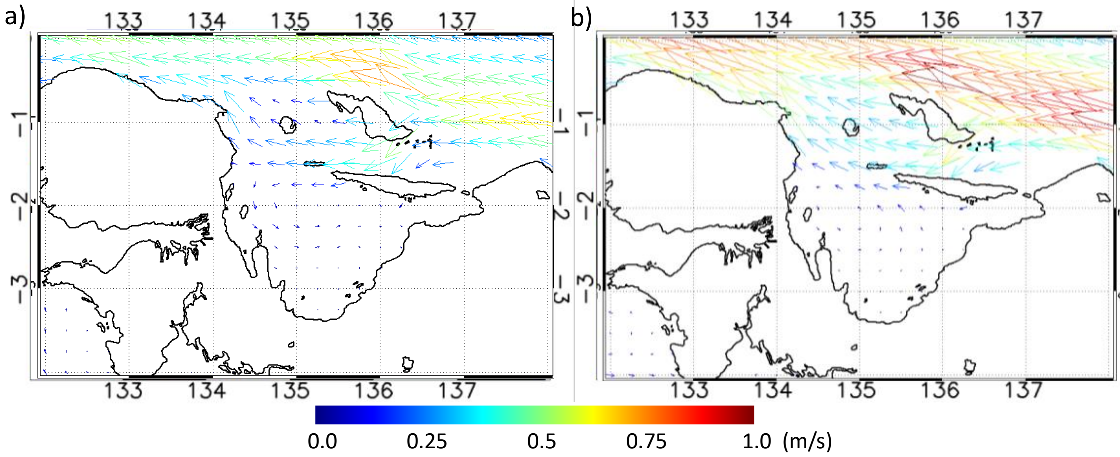

Fig. 6. Monthly climatology of current at 100 m depth in January (a) and August (b)

CONCLUSIONS

The hot Pool is used to categorize high SST episodes (>30°C) in particular areas and during specific periods (relatively long periods). Since the term "warm pool" has been used to define an area with the annual average SST distributed below 30°C in dominant, therefore "hot pool" was taken to represent the area with SST dominated above 30°C.

Under high solar radiation and low wind speed, this event is characterized by considerable daily heat gains. The constant high SST occurrence in Cenderawasih Bay, which is more than 50% of 13 years, SSTs can reach more than 30°C and are dominated by the condition of low wind speed, i.e., 80% wind speed is less than m/s along the years, also 50% solar radiation measured is more than 200 W/m^2. The current pattern at 100 m depth also shows that NGCUC does not enter Cenderawasih Bay. Thus, this indicates that Cenderawasih Bay is an isolated water. Those are the solid evidence for defining Cenderawasih Bay as the "Cenderawasih Hot Pool."

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Gmail

Abdul Rasyid <abdulrasyid.fayufi@gmail.com>

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RESEARCH PAPER

CENDERAWASIH HOT POOL: THE FREQUENT HIGH SEA SURFACE TEMPERATURE PHENOMENA AT CENDERAWASIH BAY, PAPUA

Abd. Rasyid Jalil[1*], Anindya Wirasatriya[2,3], Abdul Malik[4], Fatwa Ramdani[5,6], Puji Rahmadi[7], Gentio Harsono[8,9], Riza Yuliratno Setiawan[10]

[1]Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia
[2]Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Indonesia
[3]Coastal and Ocean Remote Sensing Laboratory, Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University, Indonesia
[4]Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Indonesia
[5]Department of International Public Policy, Faculty of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[6]Program in Economic and Public Policy, Graduate School of Humanities and Social Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[7]Research Center for Oceanography, National Research and Innovation Agency, Jakarta, Indonesia
[8]Faculty of Science and Defense Technology, Republic Indonesia Defense University, Bogor, Indonesia
[9]Hydro-Oceanography Service Center, Indonesian Navy
[10]Department of Fisheries, Faculty of Agriculture, Gadjah Mada University, Yogyakarta, Indonesia.

***Corresponding author:** abdulrasyid.fayufi@gmail.com

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ABSTRACT. The term "warm pool" refers to a body of water with the characteristic of SST exceeding 28°C within a particular area and a relatively long period in an annual circle. However, there are regions with an annual mean SST measured above 30°C, and we classified them as hot pools because of the conditions of intense solar radiation and low wind speed. One of the Hot Pool spots was found in Indonesia, in Cenderawasih Bay. The present study examines the existence of the Cenderawasih Hot Pool using long-term observation of satellite SST data. In order to learn more about their mechanisms, we also analyzed surface wind, surface heat flux, and surface current data. The results show that SSTs in Cenderawasih Bay have a 50% chance of exceeding 30°C within the 13 years of study (2013-2015). Heat input comes from strong solar radiation, i.e., 50% of solar radiation is more than 200 W/m^2. The location is also dominated by low wind speed, i.e., 80% wind speed of lower than 4 m/s, which caused the low latent loss in Cenderawasih Bay. Cenderawasih Bay is fully separated from surface currents during the dry and wet seasons since the easterly subsurface water flow does not enter the bay. The absence of strong currents prevents the mixing process, maintaining the high temperature in the surface layer. Those processes are discovered and they serve as compelling evidence to support Cenderawasih Bay as one of the Hot Pool areas within the Indonesian seas.

KEYWORDS: global climate; sea surface temperature; Hot Pool spot; Cenderawasih Bay

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INTRODUCTION

The western equatorial Pacific has a big impact on the climate. The Earth's circulation is specifically affected by the warm pool, an area with average sea surface temperatures (SST) exceeding 28°C (e.g., Wyrtki 1989; Yan et al. 1992; Clement and Seager 1999; Chongyin et al. 1999; Pierrehumbert 2000; Clement et al. 2005; Thoron et al. 2005; Herweijer et al. 2005).

On the other hand, high SST in tropical regions has attracted researchers to investigate the mechanisms since the formation of high SST requires a particular atmospheric process (e.g., Ramanathan and Collins 1991; Wallace 1992; Arking and Ziskin 1994). This process is depicted by (Waliser and Graham 1993), which shows the relation between SSTs and deep convection. They utilized highly reflective cloud information from an arbitrary examination of monthly SST data with a grid spacing of 2º (produced from combined satellite observation and in situ data) and daily visible and infrared satellite image data. The highly reflective cloud increases along with the SST as it rises from 26ºC to 29.5ºC. In contrast, the highly reflective cloud diminishes with increased SST in the temperature from 29.5ºC to 32ºC. As a result, the analysis proved that several atmospheric processes impacted SSTs below and above 29.5°C.

By taking advantage of high temporal and spatial resolution SST products derived from satellite observations (i.e., daily and ≤ 25 km×25 km), several studies (Kawamura et al. 2008; Qin et al. 2007, 2008; Qin and Kawamura 2009, 2010; Wirasatriya et al. 2015, 2016, 2017a, 2020) were able to identify high SST events (i.e., more than 30°C) in specific areas and at certain periods and define them as Hot Event (HE). In summary, they concluded that considerable daily heat gains characterize the production of HE under high solar radiation and low wind speed brought on by "remote convection" mechanisms.

(Wirasatriya et al. 2015) elaborated on the climatology of HEs in the western equatorial Pacific using the SST dataset derived from satellite microwave sensors. Throughout nine years of observation (2003-2011), they discovered 71 HE cases in the western equatorial Pacific, with the majority centered on the Solomon Islands and New Guinea Island's northern coasts, which extend eastward up to 160∞W. According to the climatology, the region has solar radiation of more than 200 W/m^2 and wind speeds of less than 4 m/s. Low wind speeds heavily influence the mechanism for HE incidence in the western equatorial Pacific. Much of the equatorial region experiences sun radiation above 200 W/m^2 during the HE periods. Low wind speeds minimize latent heat loss, which results in high SSTs and HEs in specific locations. (Wirasatriya et al. 2015) also emphasized that high solar radiation and low wind speed are much more common during the development stage and less common during the decay stage. This study also demonstrated that a rise in the long-term mean SST in the western equatorial Pacific is correlated with an increase in the frequency of HE events. HEs were responsible for 51.5% of the SSTs >30°C in the warm pool region bounded by the 29.5 °C isotherms of the climatological SST. Thus, statistically, there is a relation between the occurrence of HE and the formation of the western Pacific warm pool. Moreover, (Wirasatriya et al. 2020) demonstrated the role of HE in maintaining the warm mixed layer in the western Pacific warm pool. The frequent occurrence of HE transports heat from the surface layer to the deeper layer above the thermocline to maintain the warm mixed layer in the warm pool. Since the Pacific warm pool influences the global climate's variability through coupled ocean-atmosphere dynamics and thermodynamics (e.g., Clement and Seager 1999; Herweijer et al. 2005), this becomes an example of the contribution of high SST phenomena to regulate the global climate.

Within the Indonesian seas, the frequent appearance of high SST > 30°C has been reported by (Tita et al. 2020) in Tomini Bay and by (Swandiko et al. 2021) in the Malacca Strait. Their appearances also the high solar radiation and weak wind. The morphology of the semi-enclosed waters causes the high-frequency occurrence of low wind speed by less than 4 m/s in both areas. Besides these two areas, there is no more study on the high SST phenomena within the Indonesian Seas.

The present study demonstrates the frequent high SST occurrence (more than 30°C) in Cenderawasih Bay. Cenderawasih Bay is in northern Papua Island, part of the western Pacific warm pool. It is semi-enclosed water with a deep basin, surrounded by mountain chains (Fig. 1). Cenderawasih Bay is the habitat for whale sharks (Ihsan et al. 2018). Since the area determines warm pool definition with SST climatology higher than 28°C, we call the high-frequency occurrence of SSTs higher than 30°C in the Cenderawasih Bay the Cenderawasih Hot Pool. (Wirasatriya et al. 2015) found that the duration of HE occurrence in the western equatorial Pacific is no longer than two months since HE requires a typical condition of high solar radiation and low wind speed. Thus, it is interesting to understand the mechanisms of the high-frequency occurrence of high SST in the Cenderawasih Hot Pool.

MATERIALS AND METHODS

We used the semi-daily 11 µm SST products from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua Lv3 with a spatial resolution of 0.04º×0.04º (Esaias

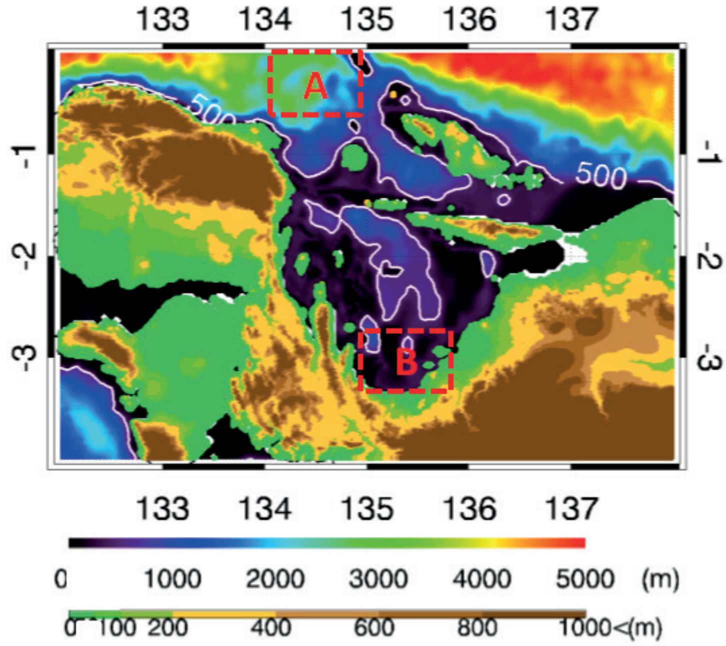

Fig. 1. Bathymetry and topography of Cenderawasih Bay. The dashed boxes A and B represent the sampling area for outside and inside Cenderawasih Bay, respectively, as shown in Fig. 5

et al. 1998) and observation period from 2003 to 2015. The MODIS SST 11 µm the Multi-Channel SST algorithm generates m by using brightness temperatures at 11 µm and 12 µm (Brown and Minnet 2009). The best accuracy was achieved by validating and testing this data against in-situ measurements (e.g., Lee et al. 2010; Qin et al. 2014; Ghanea et al. 2015).

We can obtain the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 from the following website: www.remss.com, and use it to calculate surface winds. As a result, CCMP is regarded as a Level-3 ocean vector wind analysis product. They are created utilizing data from moored buoys, satellites, and model winds. The surface wind data for spatial and temporal resolutions is 0.25º×0.25º respectively and quarter daily. This wind product has greater accuracy than other wind reanalysis data.

We used a 0.5º grid from the Objectively Analyzed Air-Sea Fluxes project to analyze daily latent heat fluxes and solar radiation (Yu and Weller 2007). The period of observation for latent heat flux is from 2003 to 2015, but for solar radiation is only from 2003 to 2009 due to the availability of the data. Global 30 Arc-Second Elevation data was used to obtain topography. Global 30 Arc-Second Elevation (GTOPO30) data was used to obtain topography[1]. ETOPO, a one-arc-minute global relief model of Earth's surface that combines land topography and ocean bathymetry[2], provides bathymetry. For oceanic parameters, we used the current reanalysis data from http://marine.copernicus.eu/ to obtain the seasonal variation of the current pattern at 100 m depth in the Cenderawasih Hot Pool.

To calculate the frequency occurrence of SST within 13 years of observation, we calculate the percentage of SST > 30°C occurrence in each grid. Since high SST of more than 30°C occurs during the condition of low wind speed (i.e., < 4 m/s) and high solar radiation (i.e., > 200 W/m^2) (Wirasatriya et al. 2015), we calculated the percentage of low wind speed and high solar radiation in the Cenderawasih Bay. Furthermore, we also calculated the percentage of low latent heat release (<120 W/m^2) to explain how wind speed influences the variability of SST. The equation for calculating the percentage is as follows:

$$\%\,(x,y) = \frac{1}{n}\sum_{i=1}^{n} pi(x,y) \times 100\,\% \qquad (1)$$

where *%(x,y)* is percentage the percentage of high SST > 30°C or percentage of weak wind speed < 4 m/s or percentage of solar radiation > 200 W/m^2 or percentage of latent heat flux < 120W/m^2 at position (x,y); p*i* is the amount of SST data > 30°C or the amount of weak wind speed < 4 m/sec or the amount solar radiation > 200 W/m2 or the amount of latent heat flux < 120W/m^2 at position (x,y). Furthermore, we also analyze the climatological mean of each parameter. To create monthly and monthly climatology, all geophysical parameters are incorporated as follows (Wirasatriya et al. 2017b):

$$\bar{X}(x,y) = \frac{1}{n}\sum_{i=1}^{n} xi(x,y,t) \qquad (2)$$

where $\bar{X}$ is monthly mean value or monthly climatology value at position (x,y), is ith value of the data at (x,y) position and time t. Next, n is the number of data in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 13 data) for monthly calculation and monthly climatology calculation, respectively. Moreover, if pixel xi is a hollow pixel, it is not included in the calculation.

RESULTS AND DISCUSSION

Cenderawasih Hot Pool

The definition of the Cenderawasih Hot Pool is described in Fig. 2, which shows the climatological mean of SST and the percentage of daily SSTs more than 30°C from 2003 to 2015 (13 years). In Cenderawasih Bay, the mean SST at the southern part of 2°S is more than 30°C, and the high SSTs are more than 50%. It means that the mean SST in Cenderawasih Bay is higher than the definition of the western Pacific warm pool which is 28°C (Wyrtki 1989), and more than 3.5 years within 2003-2015, SSTs in Cenderawasih Bay can reach more than 30°C. At the southernmost of the bay, the mean SST reaches 30.5°C, with the percentage of high SSTs being more than 70%. It has become the hottest area of Cenderawasih Bay.

In contrast, in the area outside Cenderawasih Bay, i.e., the western Pacific warm pool's offshore seas, the percentage is less than 30%. Thus, this evidence supports the definition of Cenderawasih Bay as the Cenderawasih Hot Pool. The high-frequency occurrence of high SST in Cenderawasih Bay may correspond to whale sharks' yearly appearance. (Ihsan et al. 2018) indicated the tolerance of whale sharks in high SST conditions.

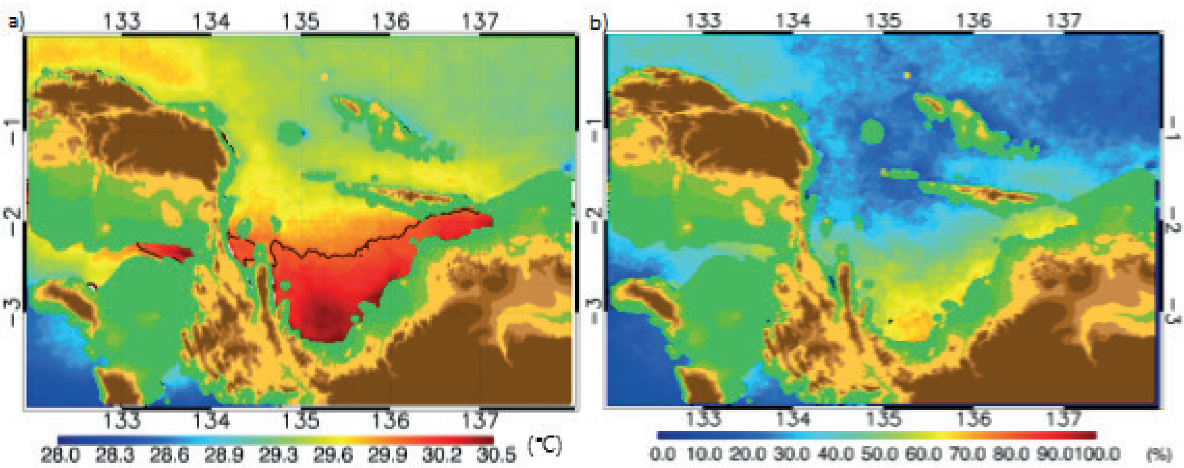

Fig. 2. Climatological mean of SST (a) and percentage of daily SSTs > 30°C during thirteen years of observation (2003-2015) (b). The black contour is 30°C

[1]https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects
[2] https://www.ngdc.noaa.gov/mgg/global/

Atmospheric Aspect of Cenderawasih Hot Pool

Fig. 3 clearly shows that low wind speed dominates Cenderawasih Bay, i.e., 80% wind speed < 4 m/s occurred during 2003-2015. This causes low latent loss in Cenderawasih Bay. For solar radiation, the percentage of high solar radiation inside and outside Cenderawasih Bay is almost similar i.e., nearly 50%, indicating that high solar radiation is not dominant in both areas. This means that, although high solar radiation does not frequently occur, the absence of strong wind speed may maintain the latent heat loss to keep the SST in Cenderawasih Bay higher than 30°C.

To investigate how low wind speed occurs in the study area, we show the monthly climatology map of surface wind during summer and winter (Fig. 4). For both seasons, Cenderawasih Bay is protected from high wind speed due to high mountain chains in the western, southern, and eastern parts. In the northern part, small islands at the mouth of the bay prevent the strong wind speed from entering the bay. Thus, the role of topography is crucial for the occurrence of constant high SSTs in Cenderawasih Bay. The same tendencies are also found at the Tomini Bay and Malacca Strait, as indicated by (Tita et al. 2020) and (Swandiko et al. 2021).

The influence of wind speed and solar radiation on the SST variation is further examined by plotting the monthly climatology of wind speed, solar radiation, and SST at areas A and B (Fig. 1), representing the areas outside and inside Cenderawasih Bay. Seasonal variations of SSTs are observed in both areas. The minimum SSTs occur during the wet and dry seasons, while the maximum SSTs during the transition season. This seasonal SST variability is similar to the other areas in the Indonesian seas, such as the Java Sea (Wirasatriya et al. 2018), Maluku Sea (Wirasatriya et al. 2019), Halmahera Sea (Setiawan et al. 2019), etc.

For the area outside Cenderawasih Bay, SST ranges from 28.2°C to 30.6°C. It is seen that the variability of SST is controlled by wind speed and solar radiation. From January to June, when wind speed decreases from 2.2 m/s to 0.3 m/s and solar radiation is more than 200 W/m2, SST increases from 28.2°C to 30.5°C. From June to October, wind speed is lower than 1 m/s. In the absence of strong wind, the low SST in July is caused by the decrease of solar radiation to a minimum.

For the area inside Cenderawasih Bay, persistent high SST is observed as the SST ranges from 30.2°C to 31.1°C. It may be due to the low wind speed of fewer than 1 m/s for years. Thus, the variability of SST is seen as ruled by solar radiation. The minimum solar radiation causes the minimum SST in July. However, the absence of strong wind prevents latent heat loss that maintains the high SST inside Cenderawasih Bay.

The oceanic aspect of Cenderawasih Hot Pool

To investigate the oceanic aspect of the Cenderawasih Hot Pool, we plotted the current patterns at 100 m depth shown in Fig. 6. A northwestward current has been identified north of Cenderawasih Bay. During the wet season (January), the speed of this current ranges from 0.5 m/s to 0.7 m/s. During the dry season (August), when the northwesterly wind disappears (Fig. 4b), the speed of the northwestward current increases. This northwestward current is known as the New Guinea Coastal Under Current (NGCUC). NGCUC is a permanent current feature at 200 m depth regardless of the wind reversals (Tsuchiya et al. 1989). Inside Cenderawasih Bay, strong currents are absent in this area, preventing the mixing process from maintaining the high temperature in the surface layer. During the dry and wet seasons, Cenderawasih Bay is fully isolated since the westward subsurface water flow does not enter Cenderawasih Bay. Thus, this isolated basin causes the Cenderawasih Bay area to be influenced mainly by the air-sea interaction process mentioned in the previous section creating Cenderawasih Hot Pool.

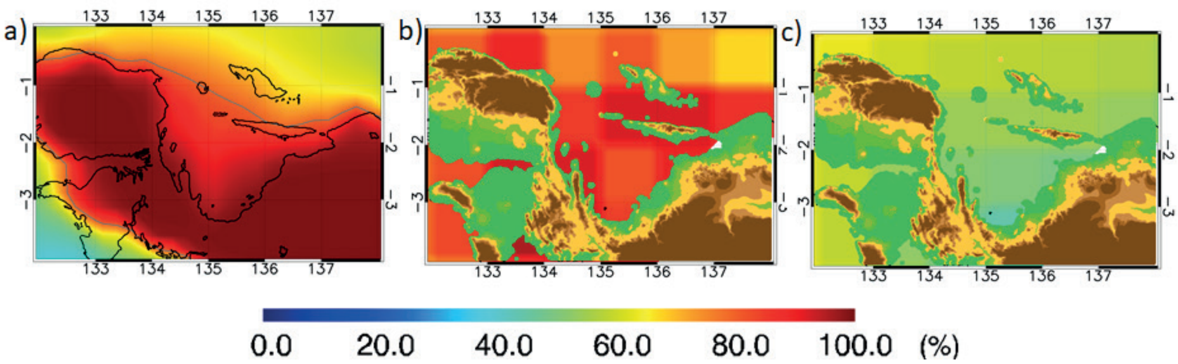

Fig. 3. The percentage of wind speed less than four m/s (a), latent heat release less than 120 W/m² (b), and solar radiation more than 200 W/m² (c)

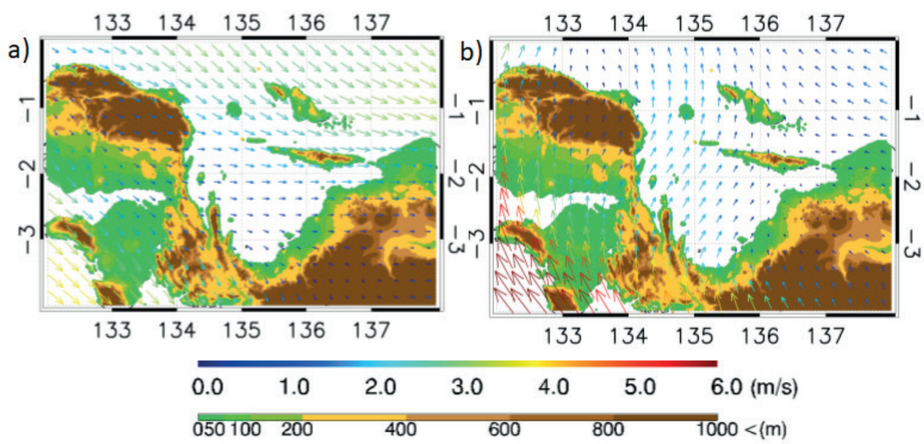

Fig. 4. Monthly climatology of surface wind speed during a) wet season (January) and b) dry season (August)

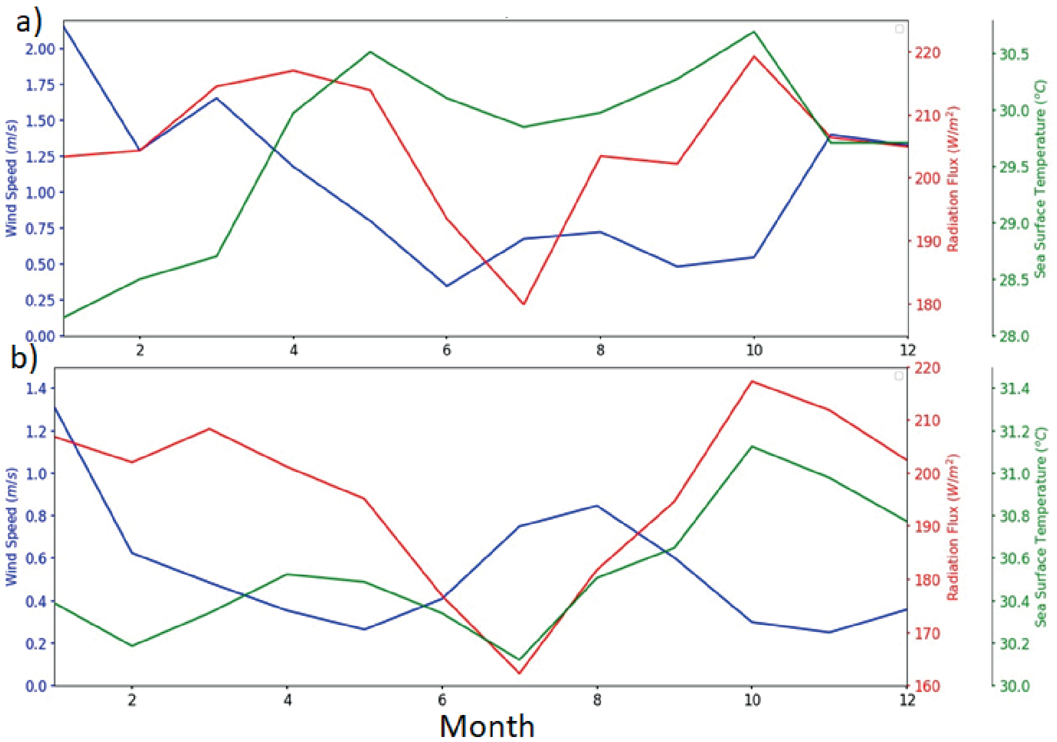

Fig. 5. Monthly climatology of SST, wind speed, and solar radiation at a) area outside and b) area inside Cenderawasih Bay, as shown in Fig. 1

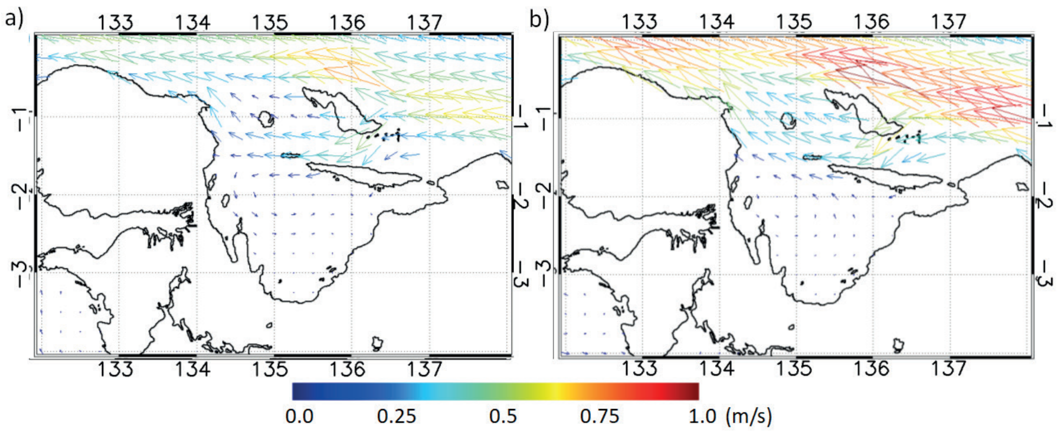

Fig. 6. Monthly climatology of current at 100 m depth in January (a) and August (b)

CONCLUSIONS

The hot Pool is used to categorize high SST episodes (>30°C) in particular areas and during specific periods (relatively long periods). Since the term "warm pool" has been used to define an area with the annual average SST distributed below 30°C in dominant, therefore "hot pool" was taken to represent the area with SST dominated above 30°C.

Under high solar radiation and low wind speed, this event is characterized by considerable daily heat gains. The constant high SST occurrence in Cenderawasih Bay, which is more than 50% of 13 years, SSTs can reach more than 30°C and are dominated by the condition of low wind speed, i.e., 80% wind speed is less than m/s along the years, also 50% solar radiation measured is more than 200 W/m^2. The current pattern at 100 m depth also shows that NGCUC does not enter Cenderawasih Bay. Thus, this indicates that Cenderawasih Bay is an isolated water. Those are the solid evidence for defining Cenderawasih Bay as the "Cenderawasih Hot Pool."

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