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Characteristics of Marine Heatwaves off West Sumatra Derived from High-Resolution Satellite Data

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Abstract: Marine heatwaves (MHWs) are high sea surface temperature (SST) periods that last for several days or weeks. They have been observed worldwide in recent decades, and they are predicted to become more frequent and intense as the global ocean's SST rises. In this paper, high-resolution satellite SST is used to investigate the characteristics of MHWs off the coast of West Sumatra. This shelf region is bordered in the west by the equatorial eastern Indian Ocean. The aim is to identify the occurrence of MHWs and quantify its metrics over the period 1982-2018. The results demonstrate that MHWs occur at least 3 to 4 times per year for the offshore and nearshore sites of West Sumatra, respectively. Moreover, the nearshore MHWs having higher proportions in terms of duration, intensity, and the number of days than the offshore MHWs. The variations in duration, frequency, intensity, and the number of days were likely caused by an imbalance in local near-surface warming and physical oceanic processes offshore. The years with the severe MHW days were those following the strong El Niño events in 1998 and 2016. This study is a significant first step in the research of MHWs in Indonesian shelf water.

Keywords: marine heatwaves, sea surface temperature, satellite, West Sumatra, Eastern Indian Ocean.

基于高分辨率卫星数据的西苏门答腊海洋热浪特征

摘要：海洋热浪是持续数天或数周的高海面温度时期。近几十年来，它们在世界范围内被观察到，随着全球海洋海面温度的升高，预计它们会变得更加频繁和强烈。本文利用高分辨率卫星海面温度研究了西苏门答腊近海海洋热浪的特征。该陆架区西部与赤道东印度洋接壤。目的是确定海洋热浪的发生并量化1982-2018年期间的指标。结果表明，在西苏门答腊的近海和近海地点，海洋热浪每年至少发生 3到4次。此外，近岸海洋热浪在持续时间、强度和天数方面比近海海洋热浪具有更高的比例。持续时间、频率、强度和天数的变化可能是由局部近地表变暖和近海物理海洋过程的不平衡引起的。发生严重海洋热浪的年份是1998年和2016年强厄尔尼诺事件之后的年份。这项研究是印度尼西亚大陆架水域海洋热浪研究的重要第一步。

关键词：海洋热浪、海面温度、卫星、西苏门答腊、东印度洋.

1. Introduction

Over the last half-century, the global sea surface temperature (SST) has risen significantly [1]. The major cause is likely to be rising anthropogenic aerosols and glasshouse gases [2]. These rapid ocean warming events have become a global concern due to their devastating impact on marine biodiversity and ecosystem worldwide and the fisheries of the region [3], [4]. The tropical Indian Ocean has the most severe warming signal around the global oceans [5], [6]. One of the recent documented extremely warm SST anomalies (SSTa) in the tropical eastern Indian Ocean was observed during the austral summer of 2015-2016

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[7], which is the warmest on record for global SST in NOAA's 137-year sequence [8].

The unprecedented extreme marine warming genesis in the eastern Indian Ocean is linked to the 2015-2016 El Niño events in the tropical Pacific Ocean [7], [9]. Following the El Niño depletion, a positive Indian Ocean Dipole Mode (IOD) formed during austral autumn and winter of 2016 [7], [9], [10]. The interaction of physical oceanic processes offshore and asymmetry in locally near-surface warming are important factors in extending extreme warming events [11], [7]. Previous research by [12] found that asymmetry in ocean warming between the two hemispheres between 2005 and 2015 likely contributed to extreme marine warming in the Southern Indian Ocean.

The large patch of warm SST rose to 3ºC above the climatological averages (Fig. 1) in most parts of the eastern Indian Ocean. This event caused coral bleaching and mortality off the coasts of West Sumatra [13] and Western Australia [14]. These bleaching reports occurred during one of the extensive global-scale bleaching events in history, which started in 2014 [1].

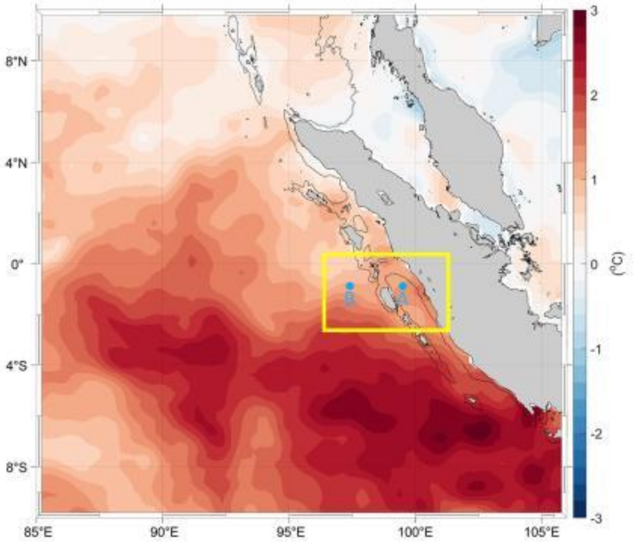

Fig. 1 Map of the equatorial eastern Indian Ocean showing the SSTa on 2 January 2016 The yellow rectangle represents the study area. Points A and B denote the nearshore and offshore locations, respectively, used to quantify the MHWs metric in Fig. 2. The thin black lines depict 500 m isobaths

The sustained positive anomalies in SST that last for days to months are referred to as marine heatwaves (MHWs) [15], [16]. MHWs are characterized by their length, frequency, strength, and spatial extent following atmospheric accords [15], [16], [17]. [17] coined the term "marine heatwave" to describe a series of widespread, persistent, and extremely warm SST events along Western Australia's coast in 2011 [18]. The MHWs off Western Australia in 2011 sparked a global initiative to characterize marine heatwaves and comprehend their statistical properties [19]. There is mounting evidence that MHWs can occur anywhere and at any time in the ocean as a result of global warming [20], [21], [22]. In addition, MHWs are expected to increase their intensity, frequency, length, and spatial extent throughout the twenty-first century [21], [22], [23]. Strong El Niño years (i.e., 1982-1983, 1997-1998, and 2015-2016) appear to enhance the physical characteristics of MHWs in the global ocean [7], [10], [23].

MHWs have been identified and studied in various parts of the world ocean. However, no study focuses on the area off the coast of West Sumatra, where Mentawai indigenous people and an ecosystem with remarkable conservation value are located [24]. In the early 1980s, the Mentawai Islands were designated as a Man and Biosphere Reserve to preserve the region's unique wildlife and human culture [24]. Therefore, this study aims to assess the characteristics of MHWs and quantify their metrics off the coast of West Sumatra. This region is one of the important biosphere reserve regions in Indonesia. SST data from January 1983 to December 2018 were analyzed to assess the climatology required to detect MHWs. We document that the severe MHW days took place following strong El Niño events in 1998 and 2016. This paper is the first study that has identified and quantified MHWs in Indonesian shelf waters.

2. Data and Methods

2.1. Satellite Data

The SST provides information on processes occurring at the ocean-atmosphere boundary layer. The high-resolution SST for January to December 2018 within the rectangular region from 96ºE to 102ºE and 0.5ºN to 3.25ºS (Fig. 1) were utilized to identify MHWs events. The SST data were obtained from the Met Office as part of the Operational Sea Surface Temperature and sea-ice Analysis (OSTIA) system [25], [26]. The OSTIA products are based on a multi-scale optimal interpolation developed for implementations in numerical weather prediction and ocean forecasting systems [25]. The OSTIA utilizes multiple satellite data, including the Group for High-resolution SST (GHRSST), the in-situ SST data available over the Global Telecommunication System, and EUMETSAT Ocean and Sea Ice Satellite Application Facility [25]. The remotely-sensed OSTIA SST data are distributed by the European Union Copernicus Marine Environment Monitoring Service (CMEMS) and can be accessed at [27]. The data are cloud-free with a horizontal spatial grid resolution of about 5 km x 5 km every day until 31 December 2018.

2.2. Detection of Marine Heatwaves

The SST is analyzed using the hierarchy metrics approach from [15], [16] to detect and quantify the MHW metrics in the study region. MHWs are described as a discrete period during which daily SST exceeds a specified threshold for at least five days in a row [15]. The 90th percentile of seasonally changing mean climatology based on a 30-year historical reference period is used as the threshold [15], [16]. The nearshore location along the Mentawai Basin has been chosen at 1.32°S and 99.62°E, while the deeper offshore waters have been chosen at 1.32°S and 97.52°E. These two stations were used to assess the physical characteristics of MHW in the study region and measure statistical occurrences (see Table 1). Following the approach by [16], the MHWs are categorized into moderate, strong, severe, and extreme events based on which temperatures surpass the local climatology.

3. Result and Discussion

3.1. Characteristics of MHWs

The daily SST and the corresponding MHW events from January 1982 to December 2018 for each nearshore and offshore site of the West Sumatra's shelf waters are shown in Fig. 2, respectively. At similar times in 1995 and 1998, the temporal SST patterns show the occurrence of extremely low temperatures below 26°C at both nearshore (Fig. 2a) and offshore (Fig. 2b) sites. These events correspond with the co-occurrence of medium to strong El Niño and the positive IOD [7]. The analysis reveals that severe MHWs events were discovered in 1995, 1998, and 2016. In 1995, severe MHWs events were identified in May and July at the offshore site. The duration of these two events was approximately 2 and 1 days (Fig. 2d), respectively. In contrast, the severe MHWs events in 1998 and 2016 were only occurred at the nearshore site.

In January 1998, the severe MHWs event took place for about 5 days, while the severe MHWs event in April 1998 lasted just about 3 days (Fig. 2e). The severe MHWs event in January and February 2016 lasted around 6 and 3 days, respectively. Apart from the nearshore severe MHWs, the offshore MHWs events in 1998 and 2016 were only categorized as moderate and strong events (Fig. 2f and 2h). Compared to previous MHW events in Australia's shelf waters, our 2016 MHW results were consistent with the previous MHW studies by [7] and [10]. Furthermore, [7] indicates that the widespread intense and extensive MHWs in 1998 and 2016 were likely driven by changes in the atmospheric conditions linked to the strong El Niño.

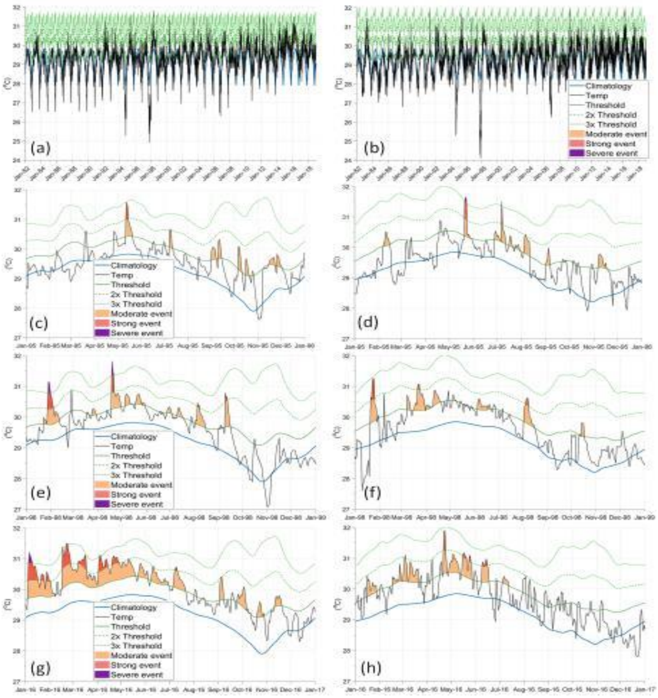

Fig. 2 The daily SST and the corresponding MHW events for each nearshore (left column) and offshore (right column) site off the coast of West Sumatra. The bottom three rows denote the snapshot of severe MHW events in 1995 (c, d), 1998 (e, f), and 2016 (g, h), respectively

The annual mean of MHW metrics for the nearshore and offshore sites off the coast of West Sumatra are summarized in Table 1. From January 1982 to December 2018, about 139 and 126 MHW events occurred in the nearshore and offshore sites, respectively. On average, there are about 4 (3) MHW events in the nearshore (offshore) each year from 1982 to 2018. The annual mean of nearshore MHW duration is 12.65 days, higher than the offshore duration of 9.37 days. The MHWs take place at least about 3.76 events per year in the nearshore and about 3.41 events per year offshore (Table 1).

The annual mean of maximum intensity somewhat similar between nearshore and offshore, though its cumulative intensity varies. The maximum nearshore intensity is 1.39°C compare to 1.38°C offshore. The annual mean cumulative intensity of MHW is 13.46°C on the nearshore and 10.02°C on the offshore. The annual mean count of days per year is 47.54 and 31.89 for the nearshore and offshore. Generally, the metrics of MHW off West Sumatra are somewhat comparable to those found in the eastern Indian ocean of the Indo-Australian basin by [7] and off eastern Tasmania by [10].

Table 1 Annual mean and decadal trends of MHW metrics for the nearshore and offshore sites off the coast of West Sumatra

Location	**Duration (days)**	**Frequency**	**Maximum intensity (°C)**	**Cumulative intensity (°C)**	**Count**
Annual Mean					
Nearshore	12.65	3.76	1.39	13.46	47.54
Offshore	9.37	3.41	1.38	10.02	31.89
Trend (per decade)					

Nearshore	0.29	0.16	0.01	0.38	3.48
Offshore	0.001	0.14	-0.004	-0.03	1.49

Fig. 3 shows the spatial metrics of MHWs from January 1982 to December 2018. It is observed that pixels with high annual mean values of duration, frequency, and counts of days occur within the shallower shelf region of the Mentawai Basin waters. The Mentawai Basin's shallower mixed layer depth seems to have intensified these MHW metrics. [7] revealed that the shallowed mixed layer depth would increase the near-surface warming temperature. In general, the annual mean of intensity higher than 1^{o}C occurred almost all over the nearshore and offshore of the study region off West Sumatra, though the most robust intensity observed well away from the coast in the open ocean (Fig. 3c). The spatial discrepancy in MHWs duration, intensity, and count of days is likely attributed to offshore physical oceanic processes [12] and the asymmetry in the local- and regional scales of near-surface warming [7].

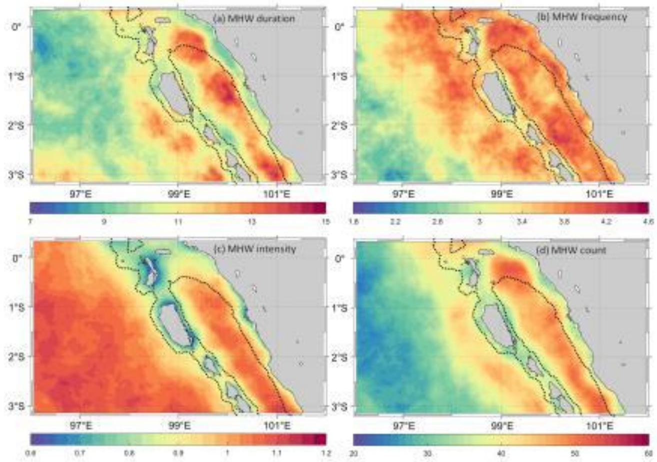

Fig. 3 The spatial distribution of MHW events showing the annual mean of duration (a), frequency (b), intensity (c), and number of days (d) along the shelf waters of West Sumatra

3.2. Trend of MHWs

The decadal trends of MHW metrics from two representative sites of the nearshore and offshore off the coast of West Sumatra are given in Table 1. The decadal trends of MHWs duration, frequency, maximum intensity, cumulative intensity, and count of days display a positive trend per decade at the nearshore location. In contrast to the nearshore, the decadal trends at offshore locations show a positive trend for the duration, frequency, and count. At the same time, they display a negative trend for maximum and cumulative intensity (Table 1). The trend of MHWs duration experienced an increase of 0.29 days per decade at the nearshore and 0.001 days per decade offshore. The decadal trend of frequency exhibits a slightly similar rate of change per decade, around 0.16 and 0.14 at the nearshore and offshore, respectively.

The decadal trend of MHWs maximum and cumulative intensity for the nearshore (offshore) site is 0.01^{o}C (-0.004^{o}C) and 0.38^{o}C (-0.03^{o}C), respectively. The count of days at the nearshore increased faster than offshore by around 50%. The decadal trends of the number of MHW days for the nearshore are about 3.48 days compare to about 1.49 days for the offshore (Table 1). The decadal trend of MHW metrics in this study is comparable with the long-term MHW study by [10] across the shelf waters off Tasmania. The decadal trend of MHWs spatial metrics distribution across the shelf waters of West Sumatra is shown in Fig. 4. The spatial patterns of MHWs' decadal trends shown in Fig. 4 were consistent with the spatial pattern of the annual mean of MHWs displayed in Fig. 3. The Mentawai Basin waters had the highest trends per decade of the MHWs metrics (i.e., duration, frequency, intensity, number of days). However, a negative trend in MHW duration and intensity was observed primarily in the offshore waters west of 98^{o} East.

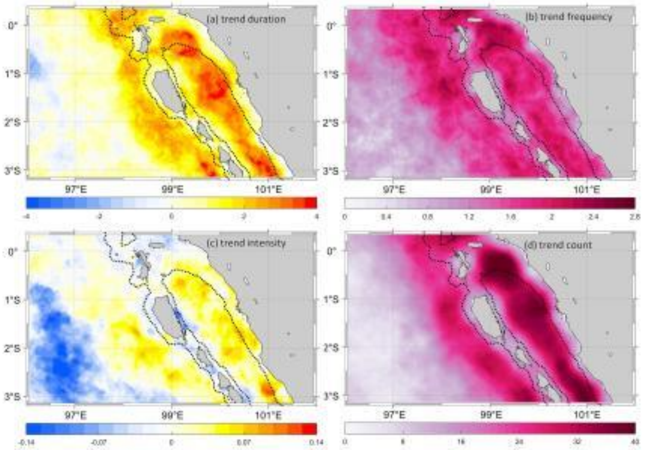

Fig. 4 The spatial distribution of MHW events showing the decadal trends of duration (a), frequency (b), intensity (c), and number of days (d) along the shelf waters of West Sumatra

4. Conclusion

The study for assessing MHW characteristics in the equatorial eastern Indian Ocean off the coast of West Sumatra is presented in this paper. The results of MHW detection using satellite SST data over a 37-year duration show a range of MHW events across the study area. Between January 1982 and December 2018, there were 139 and 126 MHW events in nearshore and offshore sites. There are approximately 4 (3) MHW events in the nearshore (offshore) per year. The annual mean state of MHWs indicates a longer duration, more robust cumulative intensity, and a greater number of days in the nearshore than in the offshore, despite a nearly identical frequency and maximum intensity between the two.

The analysis shows that MHWs detected nearshore and offshore exhibited an increasing trend in durations, frequencies, and the count of days. In contrast, the maximum intensity and cumulative intensity in the offshore region showed a slight decline. Spatially, the shallower shelf region of the Mentawai Basin waters had the highest annual mean and long-term trend of MHWs. This finding was most likely caused by a difference in the local near-surface warming and physical oceanic processes offshore. Following the discovery of MHWs off the coast of West Sumatra, a follow-up study should investigate the ocean-atmosphere interaction at local and regional scales and the coupling of the processes, which was a major driver of MHW worldwide. This study was a first step in the investigation of MHWs in Indonesian shelf waters.

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