Spatio-Temporal Characteristic Analysis of Marine Heatwaves in the Savu Sea (1982-2021)

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Abstract

Atmospheric interactions have led to a consistent rise in ocean temperatures in the Indonesian seas, exacerbated by the emergence of marine heatwaves (MHWs) that extend over thousands of kilometers. MHWs are defined as temperature anomalies above the 90th percentile of the sea surface temperature (SST) baseline for at least five consecutive days. The Savu Sea, influenced by the Indonesian throughflow that transports warm water from the Pacific to the Indian Ocean, experiences significant temperature anomalies. This study employs OSTIA L4 Marine Copernicus Global Ocean Physics Reanalysis SST data from 1982 to 2021 to analyze the frequency, duration, and intensity of MHW events in this region. Using Hobday's hierarchical approach, the study finds that MHWs in the Savu Sea lasted up to 1,170 days over 40 years, with 117 recorded events. The worst MHW event occurred in 2016, lasting 194 days with a maximum cumulative intensity of 2.0°C/year, particularly affecting the northern Savu Sea. These heatwaves significantly impact marine ecosystems, leading to coral bleaching that affects about 50% of coral colonies and threatens marine biodiversity and fisheries recovery.

Keywords : Marine Heatwaves, Sea Surface Temperature, Anomalies

INTRODUCTION

Marine heatwaves (MHWs) refer to prolonged periods of elevated sea surface temperatures (SSTs) that can significantly affect marine ecosystems. These events, which range in spatial extent from several kilometers to thousands of kilometers, have garnered increasing attention due to their escalating frequency and duration, driven by global warming (Pearce, 2011; Schlegel *et al*., 2019). MHWs are quantitatively defined by SSTs exceeding certain thresholds, typically the 90th or 99th percentile of a probability density function (Hobday *et al*., 2016). While the primary cause of MHWs is a combination of local oceanic and atmospheric processes, large-scale climate variability, such as teleconnection mechanisms, can further exacerbate their occurrence (Holbrook *et al*., 2019).

The effects of MHWs on marine ecosystems are profound, as these events disrupt ecological processes and can lead to significant shifts in biodiversity. During MHWs, heat flux dynamics are altered, particularly through changes in sensible heat flux between the ocean and the atmosphere, and increased Outgoing Longwave Radiation (OLR) due to the warmer ocean emitting more infrared radiation into space. However, the interaction between the ocean and atmosphere is complex, as factors such as cloud cover and atmospheric humidity can modulate OLR (Marin *et al*., 2022). As MHWs continue to intensify with climate change, understanding their broader ecological and socio-economic impacts is crucial (Frölicher & Laufkötter, 2018; Oliver *et al*., 2021).

In Indonesian waters, the Savu Sea is a critical region with high marine biodiversity and is directly influenced by the Indonesian Throughflow (ITF), which transports warm water from the Pacific Ocean to the Indian Ocean (Hasanudin, 1998). Changes in SSTs in this area could pose significant risks to its ecosystems. The Savu Sea is home to half of Indonesia’s marine mammal species, particularly around Lembata and Lamalera, highlighting its ecological importance

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(Dharmadi *et al*., 2010). Marine mammals, which serve as indicators of ecosystem health, are vulnerable to multiple threats including poaching, pollution, and climate change. Ensuring the survival of these species is vital not only for ecosystem health but also for human well-being.

MHWs study in the Savu Sea has been conducted by Beliyana *et al*. (2022). However their analysis only focus on the cold phase of the Pacific Decadal Oscillation in 2008-2021 (14 years). In the present study, we expand the analysis for 40 years observation (1982-2021). The primary goal of this research is to comprehensively analyze the spatio-temporal characteristics of MHWs in the Savu Sea, focusing on the frequency, duration, and intensity of MHW events. Using Hobday's hierarchical approach, this study also explores the relationship between MHWs and atmospheric and oceanic conditions, including heat flux and wind patterns. By providing a detailed understanding of MHWs in the region, the findings aim to enhance knowledge of their ecological impacts and contribute to the development of adaptation strategies to mitigate potential socio-economic consequences.

MATERIALS AND METHODS

This research is located in Sawu Waters which is between Timor Island, Alor Island, East Nusa Tenggara Island, Sumba Island, Savu Island and Rote Island which depicted in Figure 1. The research location is at the coordinate limit of -08° 00' 00" S to -11° 00' 00" S and 120° 00' 00" E to 125° 00' 00" E. This research processing methods are interpreed in Figure 2.

The data used in this study are SST data derived from OSTIA Marine Copernicus, besides that, net surface heat flux is also used, whose components consist of longwave radiation, shortwave radiation, sensible heat flux, and latent heat flux derived from The European Center for Medium-Range Weather Forecasts Reanalysis v5 (https://cds.climate.copernicus.eu/).

MHW's Event Detection

After calculating the average temperature in Sawu waters for 40 years, the detection of the most and longest occurring Marine Heatwaves events was then calculated. This event was found in 2016. This study uses OSTIA L4 Marine Copernicus Global Ocean Physics Reanalysis SST data (https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/descriptio) a spatial resolution of 0.5° x 0.5°, covering the period 1982 to 2021, to determine the frequency, average duration, and annual number of MHWs events.

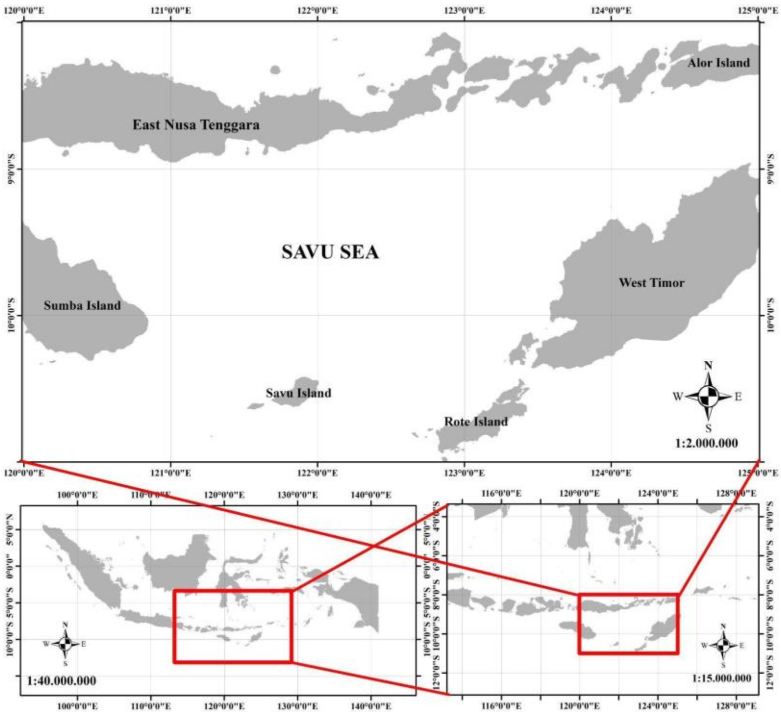

Figure 1. Location map of the Savu Sea

Based on the hierarchical approach of (Hobday *et al.*, 2016) the following formula is used to determine the frequency, average duration and annual number of MHWs events.

Based on the hierarchical approach of Hobday *et al*. (2016), MHWs analysis is assessed using the maximum intensity of MHWs to determine the difference between sea surface temperature and seasonal mean temperature. The MHWs mean intensity describes the sea surface temperature that exceeds the sea surface temperature during an MHWs event. The calculation formula used to detect the intensity of MHWs is as follows:

$$i_{max} = \max(T(t) - T_m(j))$$
$$i_{mean} = T(t) - T_m(j)$$
$$i_{var} = \sigma_{T(t)}$$
$$\text{Where } t_s \leq t \leq t_e,$$
$$j(t_s) \leq j \leq j\ (t_e),$$

σ is the standard deviation and the overbar indicates the time mean.

Net Surface Heat Flux

This research is also associated with the calculation of net surface heat flux in Sawu waters. Net surface heat flux is defined as the total heat exchange between the atmosphere and the ocean, thus affecting processes in the atmosphere and ocean. In addition, net surface heat flux can determine the actual state of ocean atmosphere interaction and climate system (Tomita *et al*., 2021). Net Heat Flux describes how much heat is collected or released by the system at a given time. In this research, several data are used for heat flux calculation. The data include Short Wave Radiation, Long Wave Radiation, Sensible Heat Flux and Latent Heat Flux which can be downloaded through ERA 5 in the radiation and heat section (https://cds.climate.copernicus.eu/ cdsapp#!/dataset/reanalysis-era5-single-levels?t ab =form).

In general, the formula for calculating net heat flux is:

$$\text{Net heat flux} = Q_{SWR} + Q_{LWR} + Q_{LHF} + Q_{SHF}$$

Note: Q_{SWR} = short wave radiation; Q_{LWR} = long wave thermal radiation; Q_{LHF} = sensible heat flux; Q_{SHF} = latent heat flux

Outgoing Longwave Radiation

Outgoing Longwave Radiation (OLR) is an index used to determine and investigate atmospheric variations related to the amount of energy emitted into space by the Earth's surface, oceans and atmosphere (). The OLR value is obtained based on radiometer scans. The National Oceanic and Atmospheric Administration (NOAA) is the source of the dataset used to determine the condition of Outgoing Longwave Radiation (OLR) (https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html). OLR represents the total radiative effect of the Earth's surface, clouds, and atmospheric gases. The OLR data used in this analysis are NOAA products, provided as daily and monthly averages.. The data used is OLR from 2016, focused on the Sawu Sea region. OLR anomalies serve as indicators of climate factors that create favorable atmospheric conditions, such as reduced cloud cover, which contribute to the development of MHWs (Benthuysen *et al*., 2021).

Wind

The wind data used in this study were downloaded from the Global Ocean Hourly Reprocessed Sea Surface Wind and Stress product derived from scatterometers and reanalysis models available on the Marine Copernicus website (https://data.marine.copernicus.eu/product/WIND_GLO_PHY_L4_MY_012_006). The data collected includes the eastward (in m/s) and northward (in m/s) wind components. The products utilized are the sea surface wind field and frictional

Table 2. MHWs Matrix (Hobday *et al*., 2016)

MHWs Matrix	Description	Unit
Annual frequency of occurrence	Total occurrence of MHWs events in one year	Events/year
Annual duration	Total duration of MHWs event in each MHWs event in one year	Day
Annual cumulative intensity	Total sum of the intensity throughout the duration of MHWs events in one year	℃

force, with a horizontal spatial resolution of 0.125 degrees. Observations from Metop-A, Metop-B, Metop-C ASCAT as well as QuikSCAT SeaWinds, ERS-1, and ERS-2 SCAT are used to calculate bias corrections to the ECMWF ERA5 reanalysis model data, with the aim of reducing persistent biases in the ECMWF wind field. Wind data is processed to determine the wind patterns that occur during the worst MHWs using the formula by Zhang *et al*. (2019):

$$V=\sqrt{u^2+v^2},$$

Note: V=wind speed; u = Eastward wind (m/s); v = Northward wind (m/s).

RESULTS AND DISCUSSION

Spatial Distribution of Marine Heatwaves (1982-2021)

Sea surface temperature is considered important to study because it is a key variable in oceanography (Sukresno *et al*., 2021);(Liu *et al*., 2021). In the Sawu Sea Waters, the average sea surface temperature over 40 years ranges from 25℃ to 31℃, with MHWs occurring when the temperature exceeds its normal threshold. The MHWs phenomenon shown in Fig. 3 includes analysis of daily intensity, frequency, and duration. This research studies MHWs from 1982 to 2021, where Fig. 2 shows that the SST exceeding the threshold is in the range of 30℃ to 31℃.

MHWs occur at specific places and times with threshold values that vary by location (Lien *et al*., 2024). Various metrics are used to describe the occurrence of MHWs in more detail, including the metrics of annual frequency of occurrence, annual duration, and annual cumulative intensity. MHWs events are measured by duration, which is the time from the start to the end of the event calculated in days. The average annual duration of MHWs events over 40 years (Fig. 4a) shows that the lowest average annual duration is located at 9 to 9.5 N and 123 E in the High Seas near West Timor Island with a value of about 20 days/year. While the highest average annual duration is located at 9 to 9.5 N and 121 E precisely near the island of Sumba with a value of about 30 days/year. This indicates that the total maximum duration value for 40 years is 1,200 days in the region.

In addition, the average annual frequency in Fig. 4b shows the annual occurrence of MHWs for 40 years with the minimum value of the average annual frequency of occurrence located at coordinates 9.5 to 10 N-S and 121 to 122 E with a total of about 1.6 events/year, this indicates that during 40 years the least MHWs occurred as many as 62.4 events in the region. While the maximum value of the average annual frequency of occurrence is located at coordinates 8.5 to 9 N and 124 to 125 E with a total of about 3.0 events/year, this indicates that over 40 years the most MHWs events occurred with a total of 71 events in the region identified as a period when sea temperatures exceeded threshold values above the 90th percentile.

The intensity of MHWs is calculated as the difference between the observed temperature and the predicted temperature based on climatological averages. This includes the maximum intensity, the average during the event, as well as the cumulative intensity (the total amount of MHWs intensity throughout its duration). Based on the results (Fig. 4c), it is known that the maximum annual cumulative intensity is in deeper waters in the mid-ocean region with a value of 2.0 ˚C/year. Meanwhile, the minimum value of 0.8 ˚C/year was found in shallower waters close to the coast. Atmospheric conditions strongly influence the temperature variability that occurs in the ocean (Adnan *et al*., 2022), where temperature is directly proportional to light intensity, if the intensity is high, the sea surface temperature will also be higher (Laosuwan *et al*., 2022). In addition to atmospheric conditions, the longer duration of heating in the dry season also contributes to making the waters warmer (Costoya *et al*., 2015).

Worst MHW Conditions in the Savu Sea

MHWs events can be identified as periods when sea temperatures exceed a threshold value above the 90th percentile of the average climatological temperature value and last for a minimum of five consecutive days. This event can last for days to months, can extend thousands of kilometers, and can penetrate several hundred meters into the deep sea (Hobday *et al*., 2016). During the 40 years that have been analyzed, the marine heatwave has the highest value with the longest duration, namely in 2016. This event occurred around February to September 2016. The SST value during this period can reach a height of up to 31°C, while the SST value the lowest is around 26.8°C. The highest value is found around March - April. The areas colored red indicate the worst MHWs periods. In 2016, the worst MHW

Research Flowchart

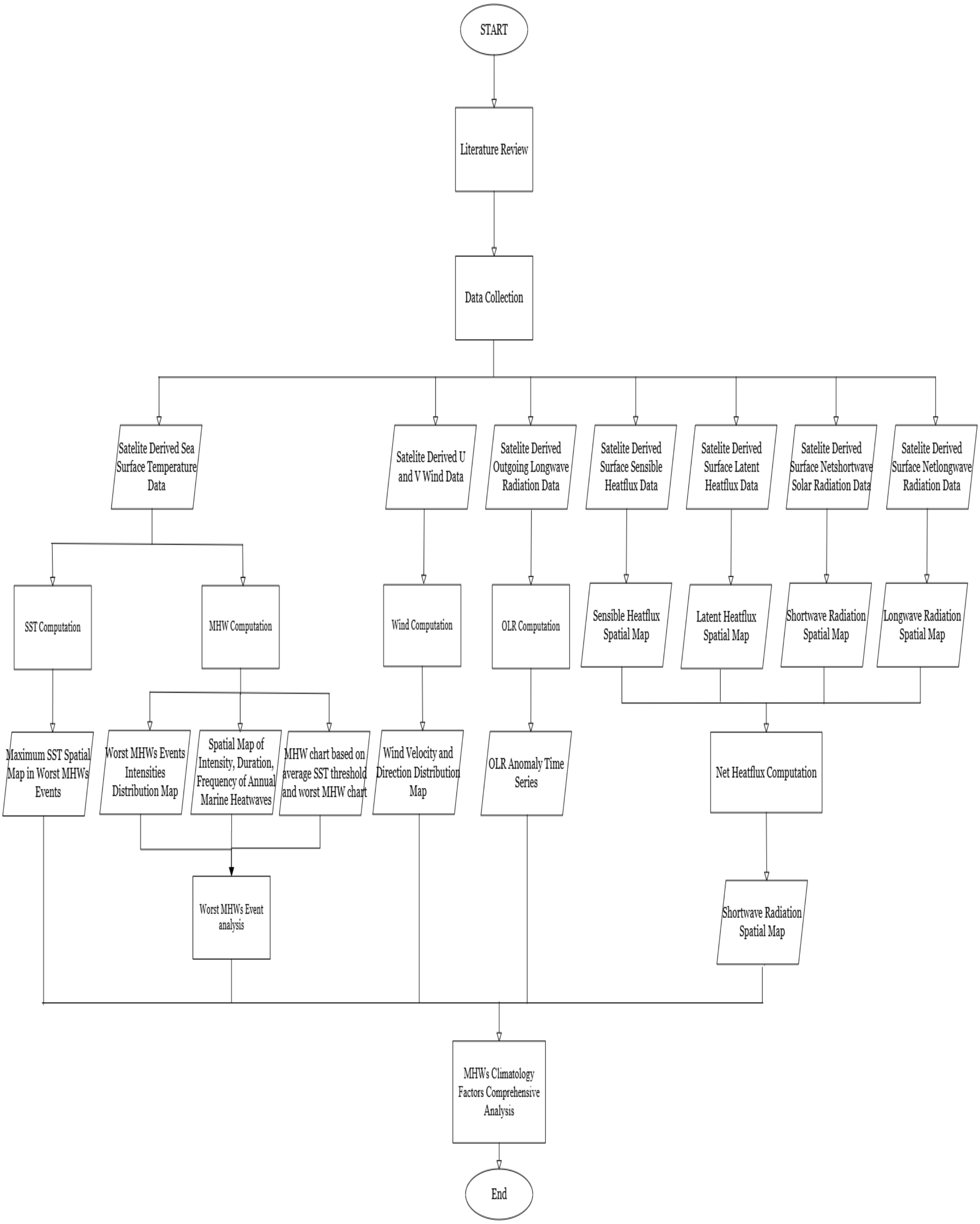

Figure 2. Research Flowchart

lasted 194 days, with 71 incidents recorded over 40 years. The worst MHWs conditions occur when SST exceeds the MHWs threshold for a significant period of time (seasonal threshold). The pink area indicates near-marine heatwave conditions, where SST approaches the MHWs threshold. MHWs incidents that occur over a long period of time and frequently can be expected to increase in the future. The consequences of this MHWs risk will have long-term, severe and widespread effects on marine ecology and socio-economic systems will increase (Holbrook *et al*., 2019).

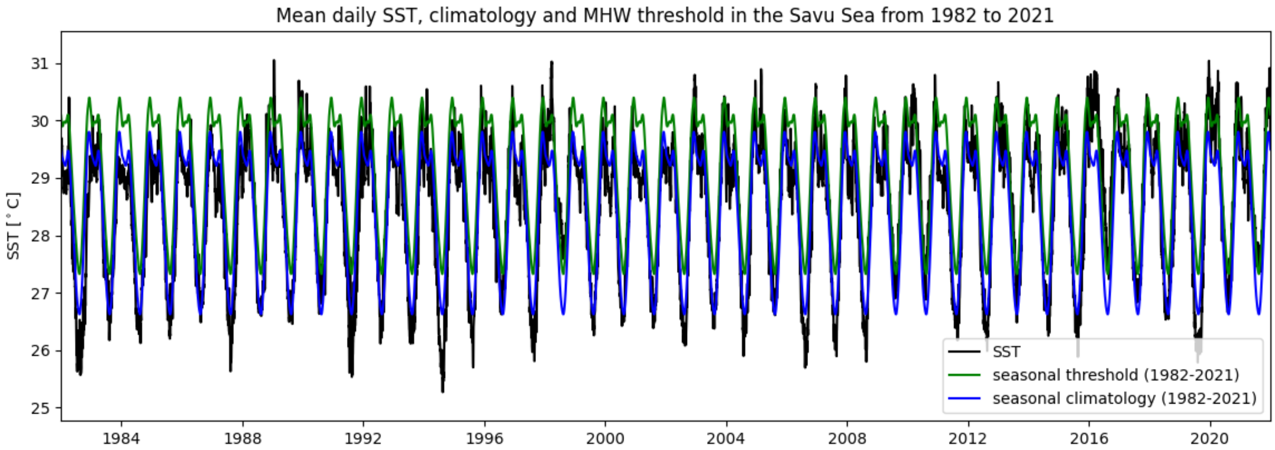

Figure 3. Mean daily SST, climatology and MHW Threshold in Savu Sea from 1982 to 2021

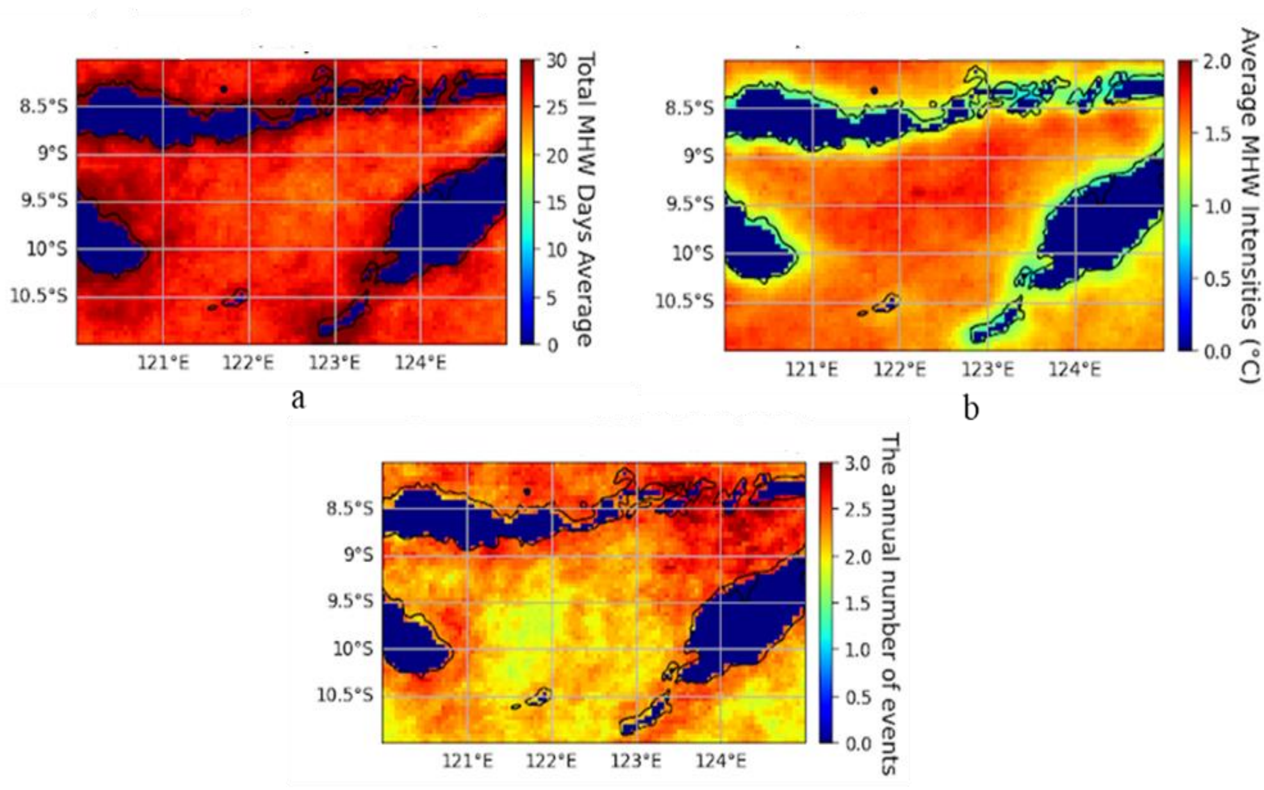

Figure 4(a). Average Daily MHWs**, 4(b).** Average Frequency of MHWs**, 4(c).** Average MHWs Intensity

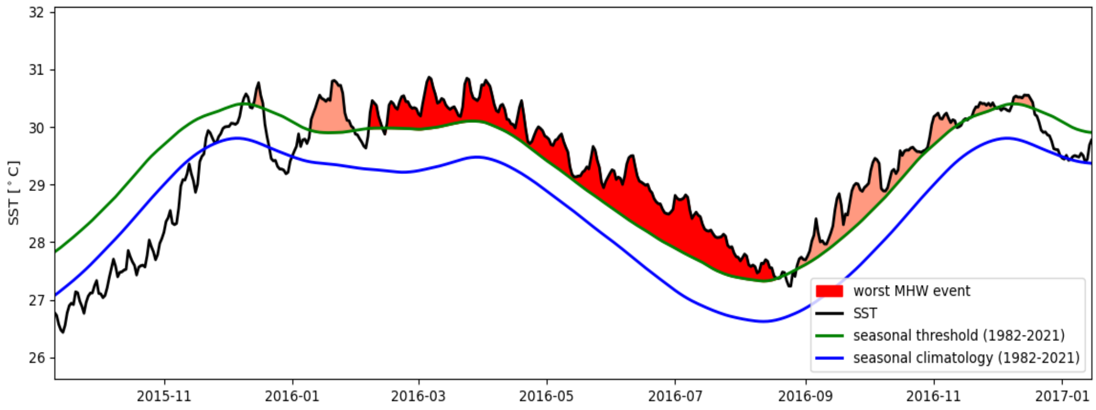

Figure 5. Average daily SST, climatology and MHWs Threshold in the Savu Sea during the worst MHWs event in the time series

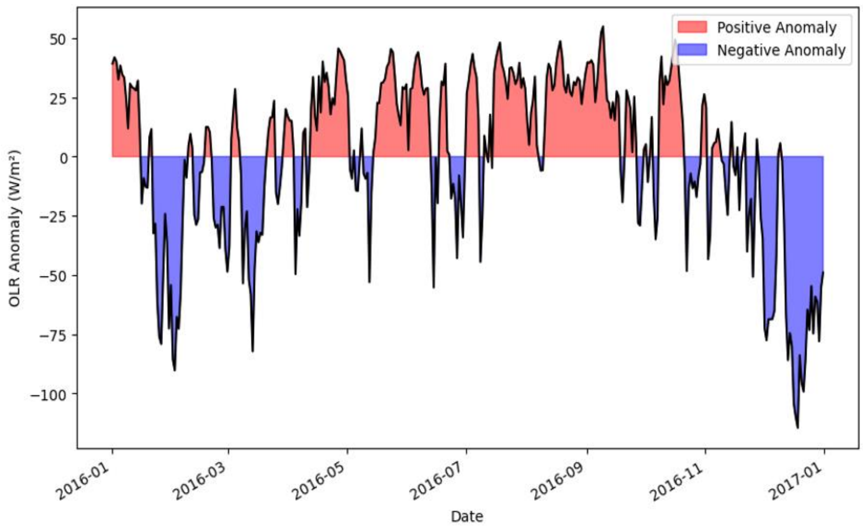

Figure 6. Time Series of OLR Anomaly over Savu Waters (-08° 00' 00” S to -11° 00' 00” S and 120° 00' 00” E to 125° 00' 00” E). Positive and negative anomalies from the 2016 MHW event are shaded in pink and blue.

Correlation of OLR with the MHW Phenomenon

The peak MHWs event in the Savu Sea occurred in 2016, this can be identified from positive OLR anomalies (very little cloud cover) and negative anomalies (more cloud cover). The positive OLR that occurred during May 2016 to September 2016 (MHWs started) was at an average of 25 and peaked at 50, indicating low cloud cover conditions. Low cloud cover allows more solar radiation to reach the sea surface. Positive OLR during peak months indicates that little sensible heat is lost from the sea surface. This indicates that the water temperature remains high due to minimal cooling through sensible heat transfer. The absence of significant cloud cover and heat loss during May to September is consistent with the peak MHWS events shown in Figure 5. (Lien *et al*., 2024).

In Savu Waters during February to October, it is characterized by the dominance of positive outgoing longwave radiation (OLR) anomalies and negative zonal wind anomalies (Figure 8.). Lack of cloud cover indicates weaker wind speeds in the area, which would reduce ocean mixing and heat transfer and lead to increased solar heat absorption, and lower winds favor reduced latent heat loss (Figure 7d). Weak wind speeds cause reduced mixing, the combination of reduced mixing, increased solar heating, and lower evaporative cooling leads to long periods of high sea surface temperatures (Dutheil *et al*., 2024).

Net Heat Flux Distribution Pattern in the Savu Sea in 2016

The highest intensity of MHWs occurred in 2016 (Figure 3). To examine the connection between atmospheric and oceanic interactions in these waters (Figure 7), the components of net heat flux (latent heat flux, sensible heat flux, longwave radiation, and shortwave radiation) are spatially analyzed. Figure 7a represents shortwave radiation, indicating positive values beginning from the northern region. This is followed by longwave radiation (Figure 7b), sensible heat flux (Figure 7c), and latent heat flux (Figure 7d). Based on the plotted net heat flux components from February 7 to August 18, 2016, it is observed that shortwave radiation reaches its peak values exceeding 230 W/m^2. The increase in shortwave radiation can reduce cloud cover, thereby enhancing the likelihood of MHWs formation. Conversely, latent heat flux is approximately ~80 W/m^2, with results indicating negative (low) latent heat flux, meaning that the energy released to cool the ocean is minimal. This condition is related to wind patterns and speed. Meanwhile, the maximum net heat flux reaches ~100 W/m^2. Upon further analysis, a consistent pattern is found between the average intensity and frequency of MHWs (Figures 4b and 4c) and the pattern of net heat flux (Figure 7e). Thus, it can be concluded that during the 2016 MHWs phase, positive net heat flux played a significant role, where the energy input to the ocean exceeded the energy loss. The increase in temperature, which may trigger MHWs, is influenced by oceanic conditions that absorb more heat.

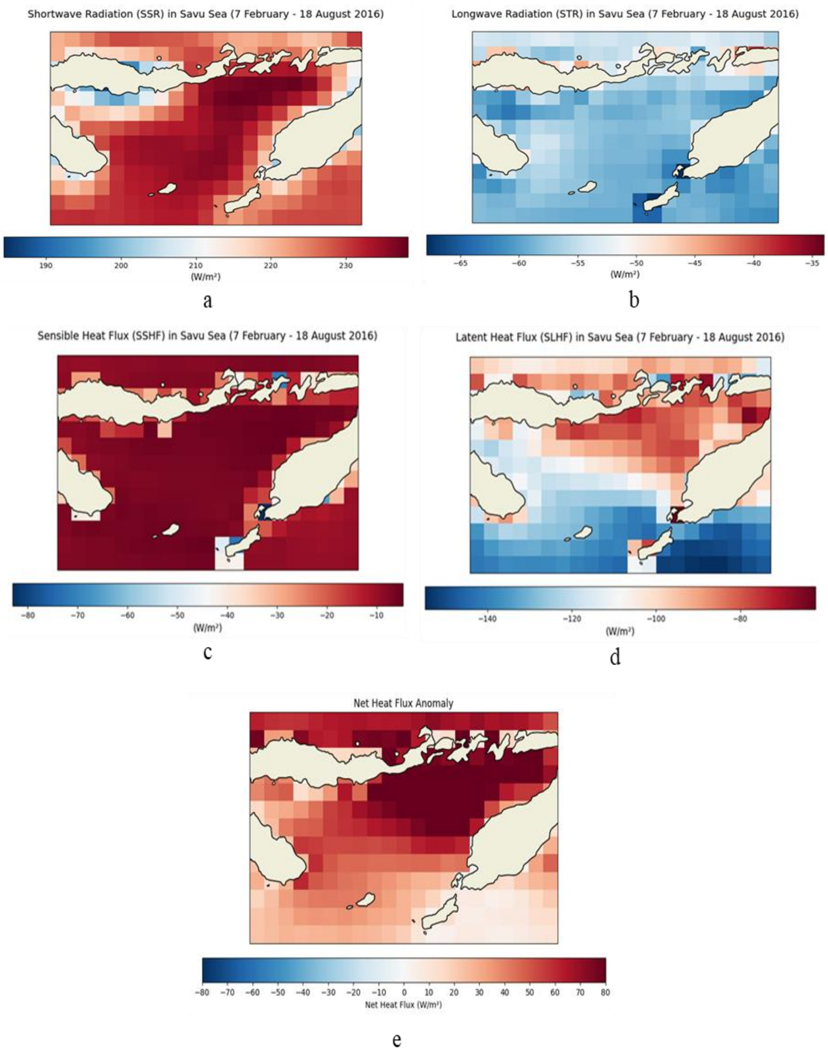

Figure 7. Net Heat Flux Conditions in the Savu Sea During the Highest MHW Period

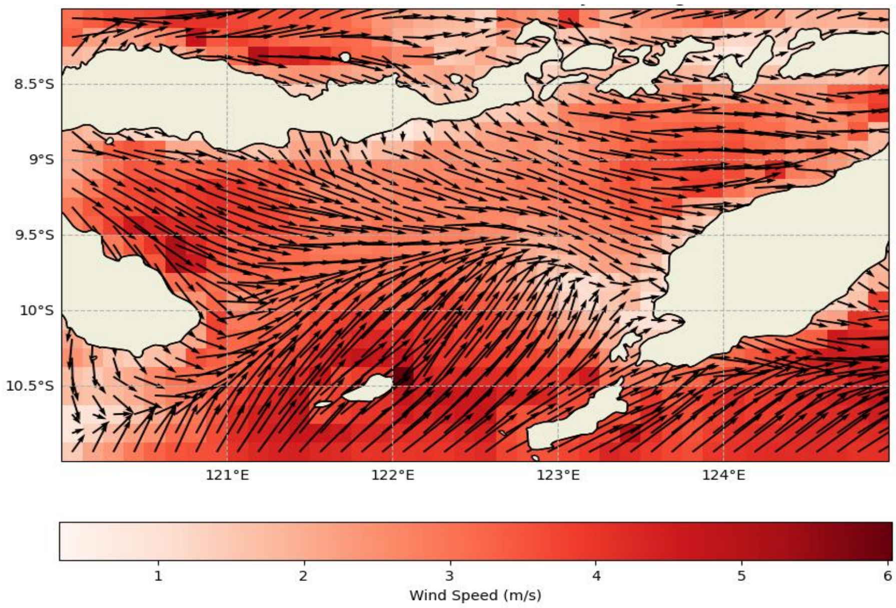

Figure 8. Wind Conditions During Marine Heatwave Event in 2016

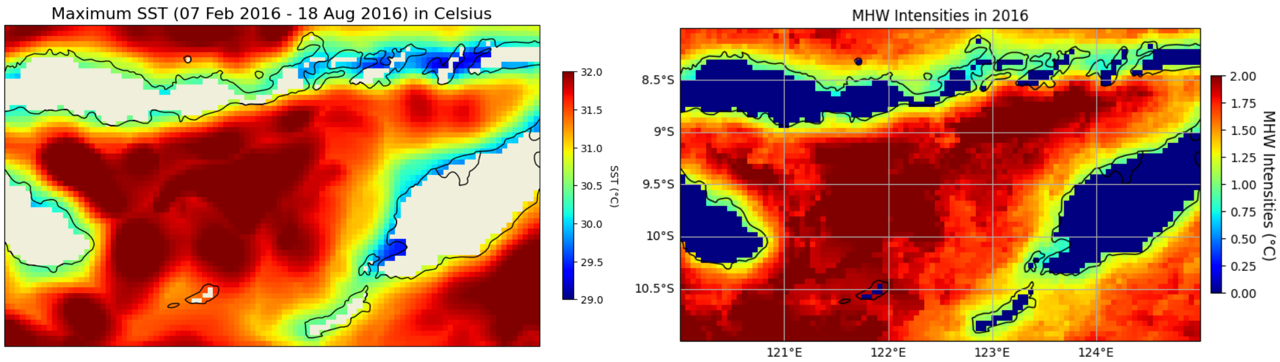

Figure 9(a). Maximum SST in 2016, **9(b)**. MHW Intensities in 2016

Correlation and Distribution of Wind to MHW in Savu Sea

Wind conditions in the Savu Sea region during the worst marine heatwaves, namely on 7 February - 18 August 2016, had a relatively weak distribution pattern, especially in the northern part of the Savu Sea (Figure 8). The wind speed tends to be small, ranging between 1-3 m/s and predominantly heading southeast. Low wind speeds reduce the rate of sea evaporation, resulting in heat accumulation on the sea surface (Roberts *et al*., 2012). This condition worsens ocean warming because heat energy cannot be dissipated effectively through evaporation. This is supported by (Figure 7d) which shows a negative anomaly of latent heat flux (SLHF), indicating a reduction in energy transfer from the ocean to the atmosphere. This reduction in latent heat flux causes heat accumulation at the ocean surface, which is closely correlated with weak wind conditions (Wu *et al*., 2020). Areas with significant negative SLHF anomalies have the potential to become MHW hotspots because heat release is disrupted, prolonging the ocean warming effect. In MHW phenomena, high sunlight intensity is often not balanced by natural cooling through evaporation, which is usually triggered by strong winds. The low wind speed as depicted strengthens the potential for a significant increase in sea surface temperatures, because moist air is released more slowly into the atmosphere. This process worsens atmospheric instability in the Sawu Sea region. Another factor to consider is the relationship between wind speed and OLR (Outgoing

Table 3. Comparative Table of Global MHW and Local MHW Trends

Aspect	Global Trends	Local Trends (Savu Sea)
MHW Frequency	increased by more than 50% since 1925	significant improvement over 27 years
MHW Intensity	significant increase since 1982	maximum measured cumulative intensity (2.0 ˚C/year)
Atmospheric influence	influenced by heat flux and circulation	closely related to the ENSO phenomenon
Ecosystem Impacts	global biodiversity change	changes in the distribution of local species

Longwave Radiation). Low wind speeds limit the formation of convective clouds (Scott *et al*., 2020), resulting in an increase in longwave radiation emitted from the sea surface.

Spatial Distribution of Maximum SST and its Relationship with Intensity

Over a 40-year period, research on Marine Heatwaves (MHWs) shows that 2016 recorded the highest peak of MHWs, with sea surface temperatures (SSTs) exceeding the 32℃ threshold lasting from February to August. This is supported by data showing significant temperature anomalies (Fig. 9a). Based on the analysis, it appears that the increase in SST correlates with the maximum intensity of MHWs in 2016. The peak of MHWs in the Sawu Sea occurred in deeper waters and far from the coastal area (offshore), with temperature intensity reaching 1.75-2℃ above normal (Fig. 9b). Previous studies have also found that MHWs with the greatest intensity in 1998 and 2016 occurred during strong El Niño phenomena, which caused sea surface temperatures to reach their maximum values (Iskandar *et al*., 2021; Mandal *et al*., 2022). The increase in sea surface temperature in transitional season I also coincides with a decrease in rainfall, as the region begins to enter the dry season, during which ocean waters receive more solar radiation than the western season. The intensity of solar radiation has a significant effect on sea surface temperature (Nababan, 2016). According to (Laosuwan *et al*., 2022), temperature is directly proportional to light intensity, if the intensity is high then the sea surface temperature will also be higher.

Spatial Distribution of Maximum SST and the Relation to Net Heat Flux

Net heat flux is the difference between heat energy received and released by the sea surface. If more heat energy comes in than comes out, then SST will increase. Regions with higher maximum SST (as seen in the top image) are most likely associated with regions that receive positive net heat flux, meaning they absorb more heat from solar radiation, the atmosphere, and other ocean-atmosphere interactions. This event will cause sea temperatures to increase and could trigger a marine heat wave. This research comprehends marine heatwave events based on net heat flux anomalies, wind direction and OLR values retrieved from 2016 worst MHWs event. Addition of other parameters are necessary to understand Marine Heatwaves events in the southern Sawu waters. Figure (b) shows the high intensity of MHWs in northern Sawu waters; this result is associated with positive heat flux anomalies in northern Sawu waters. The highest temperature above the daily value during MHWs in 2016 caused a positive net heat flux anomaly, while the high MHW intensity in southern Sawu waters was not influenced by net heat flux, because the net heat flux anomaly in the southern region was not as high as in the northern region.

Atmospheric conditions, including wind patterns and heat fluxes, play a significant role in sea surface temperature (SST) variability. Heat fluxes describe the transfer of energy from the atmosphere to the ocean surface, which directly influences sea surface temperatures. Marine heatwaves show that heat fluxes are a dominant factor in sea surface temperature variability, with interactions between El Niño and La Niña phenomena also having a significant impact. In 2016, the Sawu Sea experienced several MHWs that could be attributed to unstable atmospheric conditions. MHWs are defined as periods when seawater temperatures are above the 90th percentile of climatological conditions for at least five consecutive days. Research has shown that

MHWs can impact species distributions, primary productivity, and overall marine ecosystem health. MHWs can cause changes in marine biota communities, including declines in populations of species sensitive to high temperatures. Understanding MHW patterns can help develop adaptation strategies to protect ecosystems and support fisheries sustainability (Samiaji & Nuryadi, 2024).

Comparative Analysis with Global MHW and Local (Savu Sea) Trends

Global MHW trends show a significant increase in frequency and intensity. From 1925 to 2016, the number of annual MHW days increased by more than 50%. In addition, MHW intensity has also increased significantly since the satellite era began in 1982. Projections for the 21st century indicate that many ocean regions will reach a near-permanent MHW state, especially under the high greenhouse gas emissions scenario (RCP8) (Oliver *et al*., 2019). Meanwhile, in the Sawu Sea, research shows that MHWs have also increased in frequency and intensity. Data from 1993 to 2019 show that MHWs have increased significantly, with higher frequency and duration at certain depths (Azuga & Radjawane, 2022). This phenomenon is often associated with El Niño and La Niña events, which affect sea surface temperature patterns locally. The following is a comparative table of global MHW and local trends (Table 3)

CONCLUSION

The waters of the Savu Sea have experienced 71 MHWs from 1982 to 2021. The frequency and intensity of Marine Heatwaves (MHWs) in the north side waters is higher than other areas. The worst MHW in the Savu Sea lasted 194 days (7 February to 18 August 2016), driven by positive net heat flux anomalies and low wind speeds. The MHW event reached its peak in 2016, which was marked by a positive net heat flux phase, where the energy input to the ocean was greater than that which had to be released. An increase in temperature triggers MHWs because the ocean absorbs more heat. The positive OLR anomaly data that dominates (above number 25) during February to October 2016 and the low wind speed (1-3 m/s) during MHWs causes ocean warming because it reduces evaporation and inhibits heat transfer from the ocean to the atmosphere, especially in parts of the ocean. north of the Savu Sea. Various metrics are used to explain the occurrence of MHWs in more detail, including using the metrics of annual frequency of occurrence, annual duration, and annual cumulative intensity. The total maximum duration value is 40 years, namely 1,170 days in the area and occurs the most with a total of 117 incidents in the area. The maximum annual cumulative intensity is in deeper waters in the mid-ocean region with a value of 2.0 ˚C/year. Marine heatwaves can cause several impacts on the environment and ecosystems in waters, including coral bleaching, declining fish populations, habitat changes, and increased carbon emissions. MHWs cause significant coral bleaching, with around 50% of coral colonies affected. This bleaching reduces coral cover and slows the recovery process of coral reef ecosystems, which are crucial for supporting marine biodiversity and fisheries production. The impact of coral bleaching is also seen in the decline in fish populations, especially small and juvenile fish, which contribute to the balance of the ecosystem. This can disrupt the food chain and reduce fishermen's catches. Rising sea temperatures also affect the habitats of other marine species, increasing the risk of extinction for some species that cannot adapt quickly to temperature changes. The ocean functions as a carbon dioxide sink, but with increasing temperatures, this ability can be disrupted. MHWs can reduce the efficiency of carbon absorption by marine ecosystems, worsening the effects of climate change overall. MHWs events demonstrate the importance of stricter climate change mitigation policies. This includes reducing greenhouse gas emissions through the development of renewable energy and protecting coastal ecosystems. Given the impacts of MHWs, adaptation strategies are needed that include sustainable management of fisheries resources and protection of critical habitats to increase ecosystem resilience to climate change. This study also sets the foundation for future research, particularly in assessing the ecological impacts of MHWs on the Savu Sea's marine biodiversity and the potential socio-economic consequences for local communities dependent on these ecosystems.

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