 ISSN: 2714-8726

Marine Heatwaves and Coral Bleaching Potential in the Java Sea During the 2016 Extreme Thermal Event

Mukti Trenggono[1,2*], Denny Nugroho Sugianto[1,4], Anindya Wirasatriya[1], Mochamad Furqon Azis Ismail[3]

[1]Doctor of Marine Sciences Program, Universitas Diponegoro
Jl. Prof. Jacub Rais, Tembalang, Semarang, Jawa Tengah 50275 Indonesia
[2]Marine Science Department, Jenderal Soedirman University
Jl. Dr Soeparno, Karang Bawang, Grendeng, Purwokerto Utara, Banyumas, Jawa Tengah 53122 Indonesia
[3]Research Center for Climate and Atmosphere, National Research and Innovation Agency
Jl. Cisitu Sangkuriang, Bandung Jawa Barat 40135 Indonesia
[4]Diponegoro University SDGS Center
Jl. Prof. Soedharto, Tembalang, Semarang, Jawa Tengah 50275 Indonesia
Email: *mukti.trenggono@unsoed.ac.id

Abstract

The intense thermal event of 2016 in the Java Sea was analysed to assess the link between marine heatwave (MHW) and coral bleaching potential. We used daily sea surface temperature data from 1982 to 2023 to detect marine heatwaves using the 90th percentile threshold and generate coral bleaching heat stress in the form HotSpot and Degree Heating Weeks (DHW). The analysis was carried out in the region of the Java Sea and three reef-associated sites, namely Kepulauan Seribu, Karimunjawa, and Kangean. The results demonstrate that the 2016 event was a global marine heatwave, but that bleaching-level heat stress was geographically and temporally selective. The greatest area exposed to DHW ≥4°C-weeks was 26.3% of the entire Java Sea area, or around 182,000 km^2. Alert Level 2 was not observed, as no area achieved DHW ≥8°C-weeks. The Kangean site saw the highest bleaching potential among the three reef locations, with a maximum DHW of 4.87°C-weeks and a duration of 53 days. Kepulauan Seribu has minimal accumulated heat stress, and Karimunjawa was slightly below Alert Level 1. These results show that MHW incidence alone is not enough to represent coral bleaching potential, HotSpot and DHW give a better basis for reef monitoring and management.

Keywords: marine heatwave; coral bleaching; Degree Heating Weeks; HotSpot; Java Sea.

INTRODUCTION

The rapid warming of the oceans with anthropogenic climate change, as forecasted in the IPCC reports (IPCC, 2021; 2022), has exposed marine and coastal ecosystems to the risks of climate change impacts such as sea level rise, acidification, deoxygenation, and marine heatwave events. Marine heatwaves (MHWs) are characterized as extended periods of at least 5 consecutive days in which the sea surface temperature (SST) exceeds a climatological threshold, usually the 90th percentile (Hobday *et al*., 2016). The threshold is commonly calculated based on a long-term climatological baseline with a sliding window accounting for the seasonal cycle of the SST (Fordyce *et al*., 2019; Hobday *et al*., 2016). Previous studies (Oliver *et al*., 2019; Laufkötter *et al*., 2020; Pujol *et al*., 2022) have shown that heatwaves impact on blue ecosystems and the economy based on fisheries and aquaculture, with more profound impacts on sensitive marine habitats (e.g., coral reefs) (Fordyce *et al*., 2019; Hughes *et al*., 2017). Many reef-building corals are living close to the upper limit of their thermal tolerance, and therefore, corals are highly sensitive to persistent positive SST anomalies (Hughes *et al*., 2017). Coral bleaching is the prolonged exposure of corals to thermal stress, which results in the breakdown of the symbiosis between the coral and its photosynthetic symbionts. It was leading to loss of symbionts or photosynthetic pigments and bleaching of coral colonies (Baker *et al*., 2008; Fordyce *et al*., 2019; Genevier *et al*., 2019). Corals may be able to tolerate heat stress in the short-term, but long-term or repeated exposure to elevated temperatures can lead to reduced growth (Dias et al., 2018), impaired reproduction (Johnston *et al*., 2020; Leinbach *et al*., 2021), and increased disease susceptibility and mortality (Muller *et al*., 2018). Recent coral bleaching events worldwide demonstrate that coral reefs are increasingly subjected to repeated temperature stress (Hughes *et al*., 2018). However, the link between marine heatwaves and coral

DOI: 10.14710/ijoce.v8i3.32553
Diterima/Received : 02-04-2026
Disetujui/Accepted : 16-07-2026

 ISSN: 2714-8726

bleaching needs to be thoroughly disentangled between physical heatwave markers and biologically meaningful measures of bleaching stress.

The most common tool used for predicting coral bleaching risk is the NOAA Coral Reef Watch framework, which includes Maximum Monthly Mean (MMM), coral bleaching HotSpots, and Degree Heating Weeks (DHW) (Eakin *et al*., 2010; Heron *et al*., 2016; Liu *et al*., 2018). The HotSpot metric is a positive SST anomaly relative to the climatological MMM, indicating the most likely monthly SST anomaly at a location. For bleaching indicators, thermal stress is most relevant when the HotSpot value is equal to or above 1°C above the MMM (Liu *et al*., 2018). Daily HotSpot values associated with bleaching are then aggregated over a 12-week, or 84-day, period to determine the DHW, which accounts for both the magnitude and duration of thermal exposure (Liu *et al*., 2018). HotSpot, in this definition, is a direct index of active thermal stress. DHW is a measure of accumulated thermal stress over time, making it more closely related to bleaching intensity and the likelihood of coral mortality (Heron *et al*., 2016; Skirving *et al*., 2018, 2020). The thresholds for Bleaching Alert Level 1 and Bleaching Alert Level 2 are 4°C/week and 8°C/week, respectively (Heron *et al*., 2016). Above these thresholds, widespread bleaching and serious mortality become more likely.

The use of these Hotspot and DHW definitions is crucial for studies attempting to link marine heatwaves to the probability of coral bleaching. Marine heatwaves are not necessarily synonymous with coral bleaching, as MHW detection is based on percentile-based thermal anomalies, while bleaching stress is based on MMM-based thermal tolerance thresholds and the persistence of those thresholds over time. Thus, MHW analysis provides a physical backdrop of high ocean warming, while HotSpot and DHW translate that warming into a physiologically meaningful index of coral thermal stress (Skirving *et al*., 2020). This integrated approach allows for the detection of extreme heat events that are not only anomalous in the marine context but also sufficiently extreme and persistent to pose a potential threat to coral reef ecosystems.

Coral reef ecosystems can be found in a variety of archipelagic waters, such as shallow marginal seas, straits, and semi-enclosed basins (Burke *et al.*, 2002). These water characteristics are often found in Indonesian waters, which serve as a link between the Pacific and Indian Oceans, transmitting heat, freshwater, and mass through the Indonesian Throughflow (Hu & Sprintall, 2017; Iskandar *et al*., 2021). Indonesian waters are susceptible to repeated thermal anomalies and MHW events due to a combination of regional oceanographic conditions and underlying increases in ocean warming. High sea surface temperatures and broader climate variability, such as intense El Niño events, have been linked to previous coral bleaching events in Indonesia (Ampou *et al.*, 2017; Wouthuyzen *et al.*, 2018; Munasik *et al.*, 2025).

The Java Sea is a shallow tropical sea within the Indonesian archipelago, possessing substantial ecological and socioeconomic importance (Edinger *et al.*, 2000; Purwanto, 2003). It is bordered by densely inhabited islands and extensive coral reef systems, including the Kepulauan Seribu, Karimunjawa, and Kangean (Nugraha *et al.*, 2013; Hidayat *et al.*, 2023; Wijaya *et al.*, 2025). Characterized by pronounced seasonal variability, regional climatic influences, and elevated SST anomalies, these reefs represent critical sites for evaluating the potential consequences of extreme heat events on coral reef ecosystems. The 2016 extreme heat event is an important case study because it occurred during a period of widespread ocean warming and high climate variability, with many tropical coral reef sites experiencing increased thermal stress and bleaching (Hughes *et al.*, 2017, 2018; Setiawan *et al.*, 2017; Lough *et al.*, 2018). The 2016 warming episode has also been linked to documented bleaching impacts at several coral reef sites in Indonesia (Setiawan *et al*., 2017), suggesting that this year provides an important baseline for monitoring coral thermal stress in Indonesian waters.

Wulansari *et al*. (2026) compared satellite measurements to temperature data collected from multiple coastal stations to investigate marine heatwave events at the coastal scale along the north coast of Java and found that marine heatwaves might occur with more frequency and for a longer cumulative duration in coastal locations relative to locations farther offshore. However, the spatial and temporal aspects of heatwaves in the Java Sea, and consequences for coral bleaching potential, remain poorly studied at the basin scale. Marine heatwaves and their biological impacts are gaining more attention at global and regional scales. However, there are few studies from the Java Sea waters that specifically correlate marine heatwave data with NOAA Coastal Reef Watch bleaching stress indicators. Thus, it is crucial to distinguish areas where SSTs are substantially above the seasonally varying marine heatwave threshold from those experiencing severe bleaching stress as shown by Coral Bleaching HotSpots and Degree Heating Weeks. This is important because the MHW threshold is tied to the climatological distribution of local temperatures, whereas HotSpot and DHW are

 ISSN: 2714-8726

measures of the intensity and duration of warming above the MMM temperature. Therefore, places with similar MHW intensity may have different bleaching risks due to the accumulated heat stress from the MMM in magnitude and duration.

This study examines the likelihood of marine heatwaves and coral bleaching in the Java Sea during the 2016 exceptional thermal event. The objectives of this study were: (1) to describe the geographic and temporal evolution of the 2016 thermal event in the Java Sea; (2) the potential for coral bleaching and reef site exposure at three typical coral reef sites: Kepulauan Seribu, Karimunjawa, and Kangean. This study provides a physical and physiologically based methodological approach to evaluate the capacity of high ocean warming to cause coral bleaching in the Java Sea, by combining MHW metrics with HotSpot and DHW studies. We hope that the results of this study will help in better coral reef monitoring, regional prioritization, and proactive management methods for Indonesian coral reef ecosystems under increasing ocean warming.

MATERIALS AND METHOD

Area of Study

The research area (Figure 1) included the waters of the Java Sea. The Java Sea is part of the western Indonesian seas pathway associated with the Indonesian Throughflow system. This pathway receives volume, heat, and freshwater transport from the South China Sea through the Karimata Throughflow and redistributes water and advective heat through the Sunda Strait and the eastern boundary of the Java Sea, thereby contributing to the regional heat and volume transport balance within the Indonesian seas (Rachmayani *et al*., 2023; Xu *et al*., 2021). Our study focused on three coral-reef conservation areas, namely the Kepulauan Seribu National Park and the Karimunjawa National Park, as well as the waters around Kangean Island.

Materials

The high-resolution daily sea surface temperature (SST) V2 dataset was used with a spatial resolution of 0.25° × 0.25° from January 1985 to December 2023. The SST data were obtained from NOAA PSL. The NOAA/NESDIS/NCEI Daily Optimum Interpolation SST version 2.0 combines SST from ships and buoys with satellite data from the Advanced Very High-Resolution Radiometer (AVHRR) (Huang *et al*., 2021). The valid ocean grid for 2016 in this study has 899 cells (0.25° × 0.25° resolution), with a valid sea area of 691.820 km^2. Coral sites were adopted from a map of the distribution of spot coral reefs in Indonesia (Gusviga *et al*., 2021).

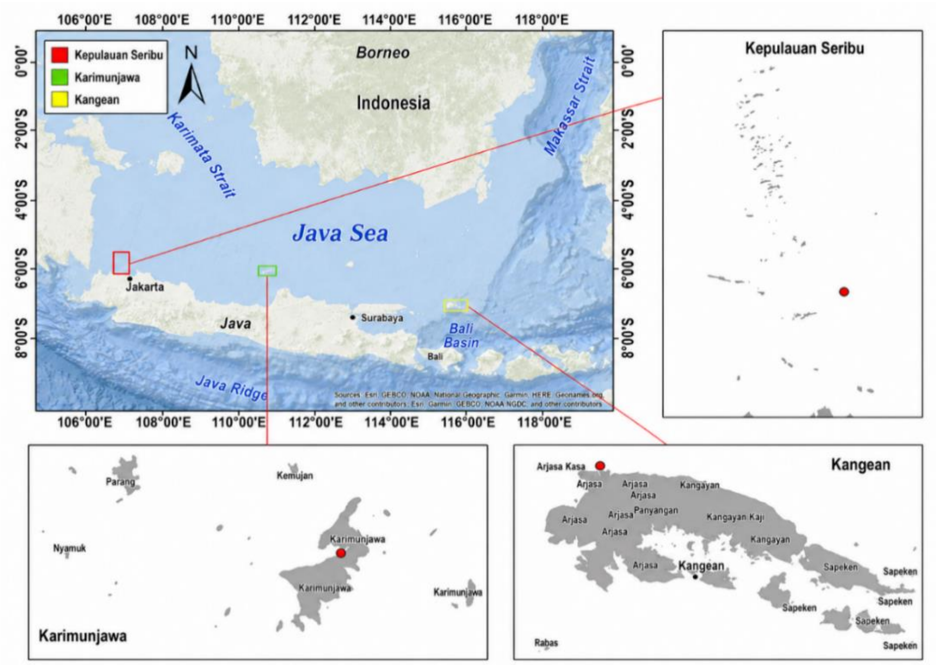

Figure 1. The map of the study. The map represents the Java Sea for the calculation of the time series of MHW properties. The area of interest in the Java Sea is located in coordinates of 105°-118° E and 2°- 8.5° S.

Detection of Marine Heatwaves

Marine heatwaves with potential for coral bleaching were identified when sea surface temperatures reached above the 90th percentile threshold. The minimum duration used is at least 5 consecutive days (Hobday *et al*., 2016). The metrics used in determining marine heat waves of this study include maximum intensity, average intensity, and the number category of MHW. The equation used in detecting MHWs is a function of the following (Hobday *et al.*, 2016) :

$$T_m(j) = \sum_{y=y_s}^{ye} \sum_{d=j-5}^{j=5} = \frac{T(y,d)}{11(y_e - y_s)}$$

Note: T_m = Climatological mean SST (°C); J = days in a year; y_e = start of year; y_s = end of year; T = sea surface temperature (°C)

$$T_{90}(j) = P_{90}(X)$$

Note: T = treshold; P_{90} = 90th percentil; X = average SST.

This percentile calculation uses an 11-day window centered on a specific day and a 41-year time series with a smoothed threshold value using a 31-day average, which were chosen to establish an adequate sample size for good percentile and climatological calculations (Hobday *et al*., 2016, 2018; Schlegel *et al*., 2017; Oliver *et al.*, 2019).

$$Average\ Duration = \frac{D_{(t_e,t_s)}}{j_k}$$

Note: D= Time (days); t_e = Starting of the Event; t_s = End of the Event; j_k = Number of events in a year

$$Average\ Intensty = \overline{T(t) - T_m(J)}$$

Note: $T_m\ (j)$= Climatological SST (°C); $T(t)$= SST from start to end of event(°C)

Marine heatwaves are classified as moderate, strong, severe, and extreme events. The classification of MHWs is based on local differences between the climatological mean and the threshold used (Hobday *et al*., 2016). This difference can be estimated at each spatial-temporal point of an SST event based on intensity measurements. The moderate category is an increase in intensity that occurs 1-2 times, strong 2-3 times, severe 3-4 times, and extreme >4 times above the threshold (Hobday *et al*., 2018). Coral bleaching potential was not inferred directly from the percentile-based MHW threshold, but was evaluated using the NOAA Coral Reef Watch thermal stress framework(Liu *et al*., 2018), particularly Coral Bleaching HotSpot and Degree Heating Weeks (Eakin *et al*., 2010; Heron *et al*., 2016; Liu *et al*., 2018).

Cumulative MHW Intensity

Cumulative MHW intensity was used to describe the accumulated magnitude of MHW exposure during 2016. After MHW days were detected at each grid cell following the 90th percentile and five-day duration criteria, the daily MHW intensity values were summed over all MHW days within 2016. Thus, cumulative MHW intensity was calculated as $CMI(y,x) = \sum I_{MHW}(t,y,x)$, where $I_{MHW}$is the daily MHW intensity at grid cell (y,x). Non-MHW days were excluded from the calculation. The unit is °C days because daily intensity values in °C were accumulated over time. This metric represents the combined effect of MHW intensity and duration (Hobday *et al*., 2016), and it differs from DHW, which is calculated from accumulated HotSpot values relative to the MMM-based bleaching threshold. Similar definitions are also used in the marineHeatWaves and heatwaveR implementations, in which cumulative intensity is reported in °C days (Schlegel *et al*., 2018).

HotSpot Analysis

The approach for the analysis of probable coral bleaching was based on the calculation of coral stress with reference to temperature. Coral bleaching happens when anomalous sea surface temperature is above the maximum SST for a long period. Earlier research defined the difference between anomalous SST and MMM (Liu *et al*., 2018; Skirving *et al*., 2020). MMM is the maximum average temperature an area normally experiences. Tropical corals live close to their thermal tolerance limits, and therefore, small increases above average maximum conditions can cause physiological stress. Thus, MMM-based HotSpots are more significant to bleaching than SST anomalies compared to the annual average or usual daily climatology. Skirving *et al.*, 2020) noted that HotSpot is an SST anomaly product that compares current SST with the MMM, which is a measure of daily heat stress on corals (Skirving *et al*., 2018).

$$HotSpot\ (t, y, x) = SST(t, y, x) - MMM(y, x)$$

Note: $SST(t, y, x)$ = daily sea surface temperature; $MMM(y, x)$ = Maximum Monthly Mean SST at grid y, x

The potential for bleaching-related thermal stress was evaluated using positive HotSpot values, particularly those ≥1°C. If the HS value is ≤ 0°C, no positive thermal anomaly above MMM is detected. HS 0 to 1°C signifies a cautious condition, while HS above 1°C represents an alert condition. This thresholding guarantees that only thermal anomalies that are important to coral bleaching heat stress are accumulated in the subsequent Degree Heating Week calculation. For each pixel, we assessed the presence of coral reefs using a combination of a published global reef mapping program, including Reefs at Risk (Burke *et al*., 2011). This was subsequently supplemented by other documented coral reef locations from reef investigations (Nugraha *et al.,* 2013; Gusviga *et al.*, 2021; Hidayat *et al.*, 2023; Munasik *et al.*, 2025; Wijaya *et al.*, 2025).

Degree of heating week calculation

Degree of heating week is an accumulated measure of Hotspot that reflects the intensity and duration of thermal stress (Heron et al., 2016; Liu *et al*., 2018) over a period of 12 weeks, or 84 days (in °C-weeks) (Eakin *et al*., 2010; Lachs *et al*., 2021; Liu *et al*., 2018; Skirving *et al*., 2020). To determine the extent of potential coral bleaching events, we used HS ≥ 1°C (Liu *et al*., 2018; Skirving *et al*., 2020). Coral bleaching occurs when corals are exposed to elevated thermal stress over extended periods. The determination of DHW values involved multiplying the duration of MHW at weekly HS criteria-fulfilling average intensity by the average intensity of MHW, following the equation below:

$$DHW_i = \sum_{n=i=83}^{i} \left(\frac{HS_n}{7}\right), where\ HS_n \geq 1$$

The division by 7 is done because the final unit is °C-weeks, not °C-days. The NOAA CRW uses a 12-week window, or about three months, because bleaching is triggered not just by momentary heat, but by the accumulation of heat stress over a considerable period. NOAA explains that the DHW represents the accumulation of heat over the previous 12 weeks; at each time step, the old value exits the window, and the new value enters as a running sum. In our study, the DHW was calculated from the full time series covering the period 1982–2023, then excluded the year 2016, so the DHW calculation for 2016 was not truncated at the beginning of the year.

Evaluation of thermal stress levels

Following the DHW computation, the heat stress level is estimated according to the NOAA Coral Reef Watch (CRW) thresholds (Figure 2). In the classical CRW method, a DHW of 4°C-weeks begins Bleaching Alert Level 1, and a DHW of 8°C-weeks begins Bleaching Alert Level 2. NOAA suggests that the chances of major bleaching increase to Alert Level 1, and the likelihood of severe widespread bleaching and significant coral mortality is more likely at Alert Level 2 (Eakin *et al*., 2010; Heron *et al*., 2016; Liu *et al*., 2018). Thermal stress levels were categorised based on the maximum DHW reached in 2016. We classified grid cells with the highest DHW < 4°C-weeks as below the bleaching warning level. Grid cells with 4 ≤ DHW < 8°C-weeks were designated as Alert Level 1, with increased bleaching potential. Grid cells with DHW ≥ 8°C-weeks were assigned to Alert Level 2, indicating severe bleaching-level heat stress and an increased chance of widespread bleaching and mortality. These categories are based on the NOAA Coral Reef Watch thermal stress framework and were used to assess the regional and temporal distribution of coral bleaching potential in the Java Sea.

 ISSN: 2714-8726

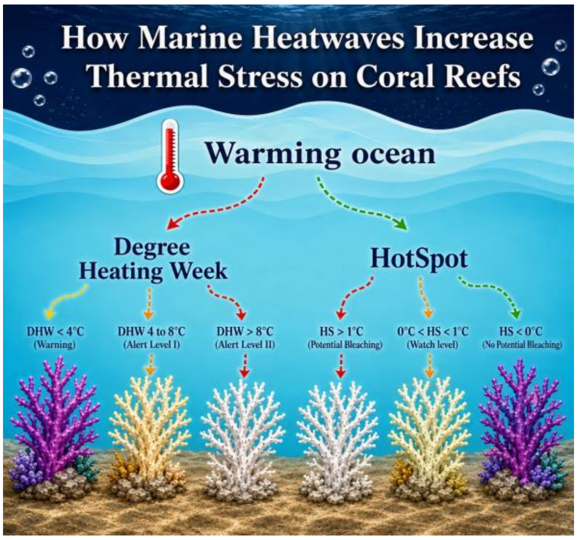

Figure 2. Diagram illustrating the approach of marine heat wave hotspots and degree heating weeks in determining the potential for coral bleaching during heatwave events

MHW exposure and bleaching-level exposure are significant because DHW is conceptually more closely connected to bleaching risk than MHW intensity or MHW days alone. According to Skirving *et al.*, 2020, CRW products like MMM, HotSpot, and DHW are developed to measure heat stress associated with bleaching.

RESULT AND DISCUSSION

Spatiotemporal Evolution of The 2016 Thermal Event

The 2016 thermal event in the Java Sea was spatially extensive, but its bleaching potential was not uniform across the domain. The MHW metrics showed that large parts of the Java Sea experienced strong and persistent warming during 2016 (Figures 3a and 3c). This is in agreement with the broad definition of MHWs as distinct warm episodes which may be described in terms of their intensity, duration and spatial breadth (Hobday *et al*., 2016, 2018). However, when we used measurements important to bleaching, the spatial pattern changed. The distribution of HotSpot and DHW was more restricted than the MHW measures, notably in the central-eastern to eastern Java Sea (Figures 3b and 3d). This difference emphasises that MHW intensity is not directly comparable with coral bleaching potential, because MHWs are defined relative to the seasonal threshold based on a percentile, while coral bleaching heat stress is relative to the thermal threshold based on the MMM, adopted in the NOAA Coral Reef Watch framework (Heron *et al*., 2016; Liu *et al*., 2018; Skirving *et al*., 2020).

The difference between MHW intensity and HotSpot is essential for interpreting the 2016 event in the Java Sea. High maximum MHW intensity regions did not always match with high HotSpot values. This is because maximal MHW intensity is computed as the deviation from the daily climatological MHW threshold, whereas HotSpot is computed as the SST deviation from the warmest climatological condition relevant to coral thermal tolerance. Such differences between physical MHW metrics and coral bleaching heat-stress metrics have also been noted in prior coral reef studies where MHWs provide the physical context of warming, but HotSpot and DHW provide a more direct estimate of bleaching-relevant heat stress (Fordyce *et al*., 2019; Genevier *et al*., 2019; Skirving *et al*., 2020). Therefore, the Java Sea results support the idea that not all MHW-affected areas necessarily experience the same level of ecological heat stress. Cumulative MHW intensity was high in several parts of the western to eastern Java Sea (Figure 3c), indicating that some areas experienced a substantial accumulation of MHW-related heat. However, the maximum DHW pattern was more localized than the MHW pattern (Figure 3d). In the Java Sea, the strongest bleaching potential occurred where HotSpot conditions persisted long enough for DHW to reach ≥4°C-weeks, not simply where MHW intensity was highest.

 ISSN: 2714-8726

The area exposure curves indicate that MHW conditions were widespread and recurrent in the Java Sea during 2016 (Figure 4), with some episodes covering a large portion of the valid ocean grid (Black curve). However, the heat stress relevant to bleaching was more temporally limited. Hotspots > 1°C were primarily present in January and March–April, and were strongest in May (Orange curve), while DHWs ≥ 4°C-weeks reached a maximum coverage of approximately 26.3% (equivalent to approximately 182,000 km^2 of the total valid sea area of 691.820 km^2) in late May through June (Red curve). This suggests that the potential for bleaching was limited to specific periods, particularly May–June. No areas reached DHWs ≥ 8°C-weeks, so the 2016 event resulted in Alert Level 1 conditions in parts of the Java Sea but did not reach Alert Level 2. This temporal pattern suggests that widespread MHWs do not always translate into bleaching-level heat stress; the potential for bleaching arises when the Hotspot anomalies relative to the MMM are strong and persistent enough to accumulate into DHW. DHW has been more related to the severity of coral mortality and bleaching (Eakin *et al*., 2010; Heron *et al*., 2016; Liu *et al*., 2018). The Java Sea experienced bleaching-relevant heat stress in 2016, but it was moderate and spatially specific, not severe and basin-wide. This is consistent with broader evidence that 2016 was a time of increased coral thermal stress across many tropical reef regions (Hughes *et al.*, 2017, 2018; Lough *et al.*, 2018). However, the Java Sea response in this study was more limited than the severe bleaching conditions reported in some other tropical reef systems. Thus, the 2016 event in the Java Sea should be interpreted as a spatially selective Alert Level 1 bleaching-potential event, not as a basin-wide Alert Level 2 event.

The persistence maps show that MHW exposure lasted for many days across much of the Java Sea, with several grids experiencing more than 100 MHW active days (Figure 5a). However, the number of days with HotSpot >1°C was much lower and concentrated mainly in the central-eastern to eastern Java Sea (Figure 5b). Days with DHW ≥4°C-weeks were even more spatially restricted (Figure 5c). These results indicate that persistence of MHW conditions did not automatically translate into persistence of bleaching-level heat stress. This pattern supports the methodological distinction between MHW persistence and bleaching-level heat stress persistence.

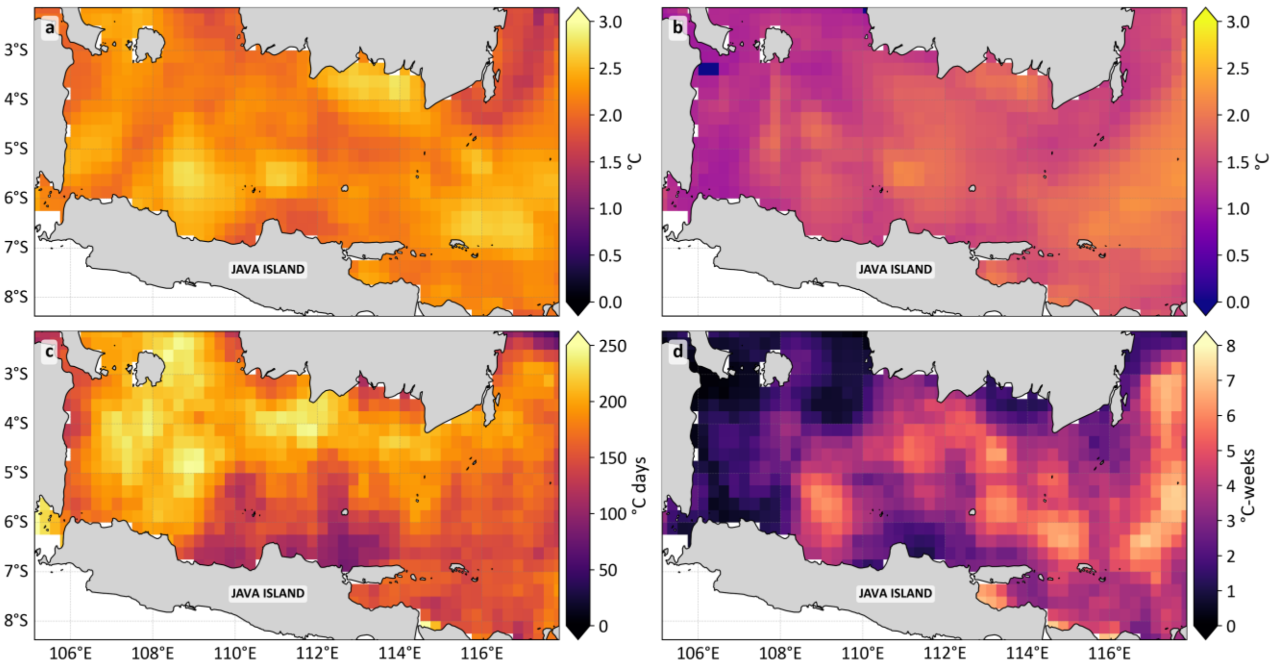

Figure 3. MHW Metrics and Coral Bleaching Heat-Stress Metrics in the Java Sea (2016). a. Maximum MHW Intensity; b. Maximum Coral Bleaching HotSpot; c. Cumulative MHW Intensity; d. Maximum Degree Heating Weeks. This figure shows the pathway from oceanographic heat events to potential ecological heat stress on corals.

 ISSN: 2714-8726

MHW active days describe how long SST remained above the percentile-based MHW threshold, while DHW ≥4°C-weeks days describe how long a grid remained under accumulated bleaching-level heat stress. This pattern supports the methodological distinction between MHW persistence and bleaching-level heat stress persistence. MHW active days describe how long SST remained above the percentile-based MHW threshold, while DHW ≥4°C-weeks days describe how long a grid remained under accumulated bleaching-level heat stress.

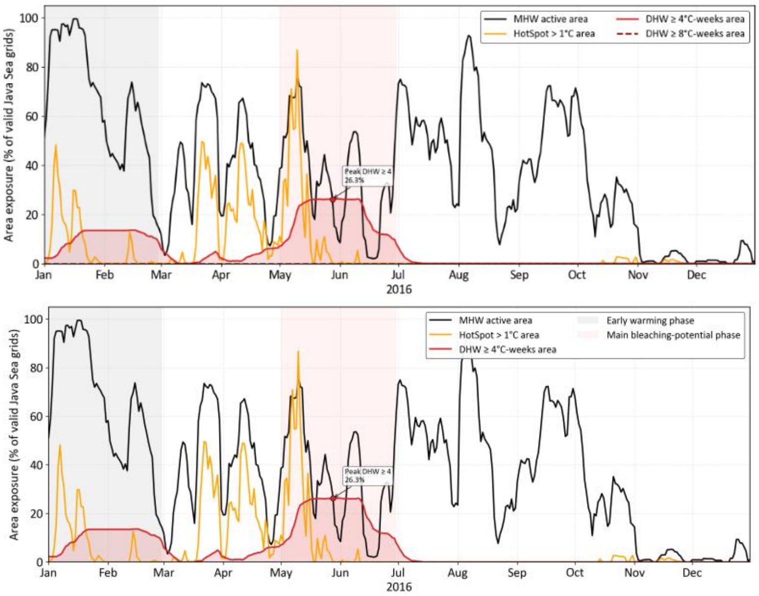

Figure 4. Area Exposure to MHW and Coral Bleaching Heat Stress in the Java Sea (2016). The black line shows the percentage of valid Java Sea grids experiencing active MHW conditions, the orange line shows HotSpot >1°C area, and the red line shows DHW ≥4°C-weeks area. Gray shading indicates the early warming phase (January–February), while pink shading indicates the main bleaching-potential phase (May–June). DHW ≥8°C-weeks is not shown because no valid Java Sea grid reached this threshold during 2016. The red shaded area under the curve highlights the temporal extent of DHW ≥4°C-weeks exposure.

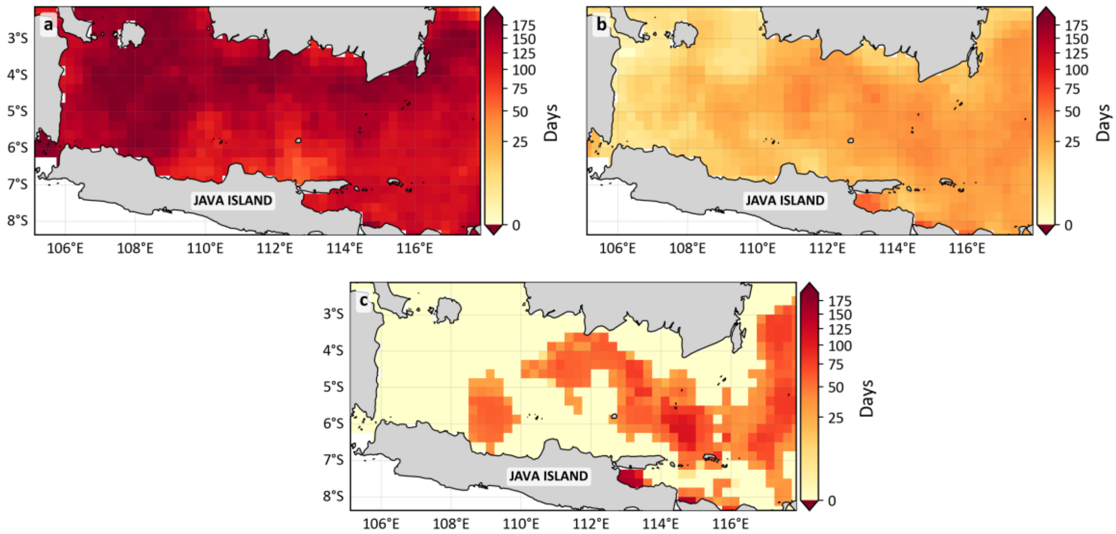

Figure 5. Event Persistence of MHW and Coral Bleaching Heat Stress in the Java Sea (2016). a. MHW Active Days; b. HotSpot > 1°C Days; c. DHW ≥ 4°C-weeks Days. This figure shows how long each grid in the Java Sea experienced exposure to MHW active days, HotSpot > 1°C days, and DHW ≥ 4°C-weeks days during 2016. All three panels use in the same unit, namely days.

Figure 6 shows the relationship between marine heatwave metrics and coral bleaching potential based on DHW on valid grids of the Java Sea in 2016. Joint distribution analysis demonstrated that MHW and heat stress bleaching metrics are not directly interchangeable during the 2016 event. The 2016 MHW represented a widespread physical extreme in the Java Sea, but the bleaching potential was more strongly explained by HotSpot and DHW. Maximum MHW intensity had only a weak positive relationship with maximum DHW (Figure 6a), while cumulative MHW intensity had almost no relationship with DHW (Figure 6b). Conversely, maximum HotSpot was highly positively correlated with maximum DHW, which is not surprising since DHW is calculated based on the accumulation of HotSpot anomalies above a bleaching-relevant threshold in a 12-week period (Heron *et al*., 2016; Liu *et al*., 2018; Skirving *et al*., 2020). Results suggest that in the case of MMM the potential for bleaching is more related to heat stress than to MHW intensity or accumulation alone.

The weak relationship between cumulative MHW intensity and DHW is an important result of this study. Although both metrics appear to represent heat accumulation, they accumulate heat relative to different thresholds. Cumulative MHW intensity accumulated anomalies above the MHW threshold, whereas DHW accumulated HotSpot anomalies above the bleaching-relevant MMM +1°C threshold. This explains why a grid can experience long or cumulative MHW exposure without reaching high DHW. In the Java Sea, bleaching potential was better explained by HotSpot and DHW than by MHW intensity or cumulative MHW exposure alone.

Figure 7 complements Figure 6. While Figure 6 shows the relationships between metrics continuously, Figure 7 groups grids into four risk quadrants based on combinations of high or low intensity and long or short duration. The results of this quadrant analysis are consistent with Figure 6. Figure 6 shows that the relationship between Maximum MHW intensity and DHW is only weak to moderate, while Cumulative MHW intensity has almost no correlation with DHW. Figure 7 illustrates how the 2016 extreme heat event transformed into a heat stress relevant for coral bleaching in the Java Sea. The quadrant analysis divided valid ocean grids into four groups based on maximum MHW intensity and the number of active MHW days (Figure 7a). The results indicated that Java Sea grids that reached Alert Level 1 were not simply those with the longest MHW durations. Rather, they were more frequently associated with high MHW intensity. The highest mean maximum DHW was found in the high-intensity–short-duration quadrant, at 4.48°C-week, thus exceeding the Alert Level 1 threshold (Figure 7b). In contrast, the low-intensity–long-duration quadrant remained below the alert threshold, with a mean maximum DHW of 3.05°C-week. This suggests that prolonged MHW exposure in the Java Sea does not necessarily result in a high bleaching potential if the warming is not strong enough to exceed the thermal bleaching threshold. Therefore, the 2016 bleaching potential in the Java Sea is more related to high-intensity local warming than to the duration of the MHW alone.

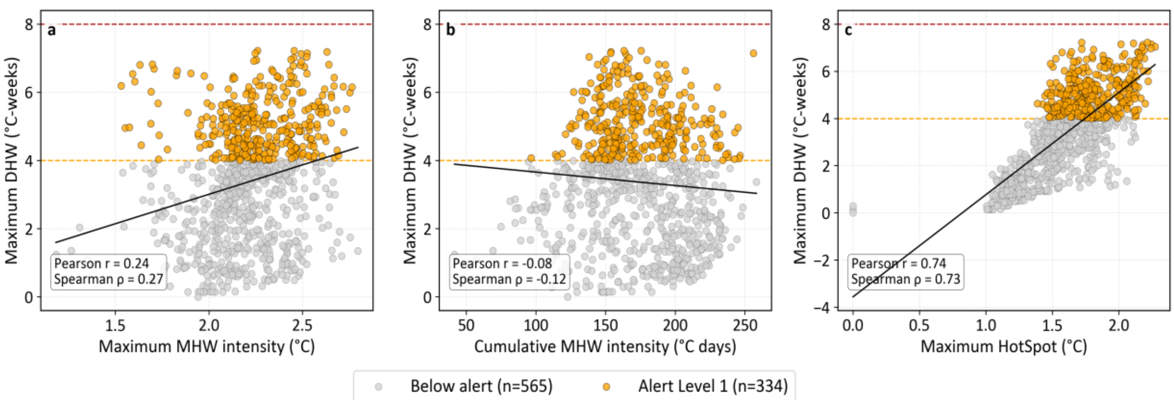

Figure 6. Joint Distribution of MHW Metrics and Bleaching Heat Stress in the Java Sea (2016). a. Maximum MHW intensity vs Maximum DHW; b. Cumulative MHW intensity vs Maximum DHW; c. Maximum HotSpot vs Maximum DHW. The Y-axis in all panels is Maximum DHW (°C-weeks), while the X-axis is different for each panel. Gray dots indicate grids with DHW < 4°C-weeks or below alert, while orange dots indicate grids with 4 ≤ DHW < 8°C-weeks or Alert Level 1. The orange dashed line indicates the threshold of DHW = 4°C-weeks, while the dark red line indicates DHW = 8°C-weeks. The number of grids with DHW below the alert threshold is 565 grids, while the number of grids entering Alert Level 1 is 334 grids.

 ISSN: 2714-8726

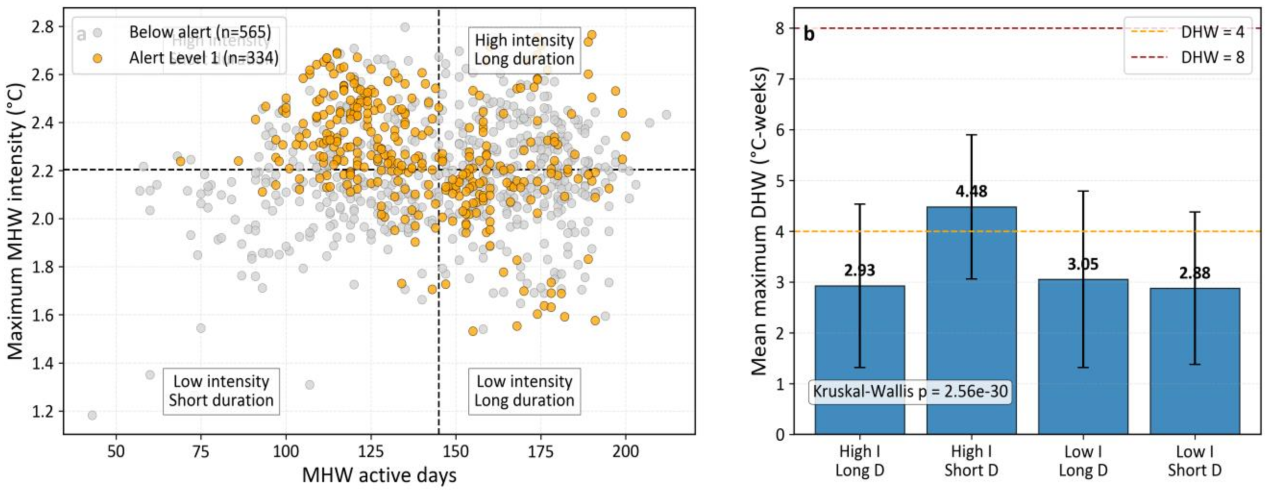

Figure 7. Quadrant Analysis of MHW Intensity–Duration and Bleaching Heat Stress in the Java Sea (2016). a. Intensity–Duration Risk Matrix; b. Mean DHW by Quadrant. Panel a shows the distribution of each valid ocean grid in the Java Sea. The X-axis is the number of active MHW days, while the Y-axis is the maximum MHW intensity. Gray dots represent grids that remain below the bleaching alert threshold, while orange dots represent grids that reach Alert Level 1, i.e., grids with DHW ≥4°C-weeks. Panel b summarizes the average maximum DHW from four grid groups formed from the combination of DHW intensity and duration.

Coral Bleaching Potential and Reef-Site Exposure

Figure 8 shows the regional extent of bleaching-level heat stress, defined as a grid with maximum DHW ≥ 4 °C-weeks. The spatial cluster analysis shows that bleaching-level heat stress in 2016 was not randomly distributed across the Java Sea. Grids with maximum DHW ≥4°C-weeks formed several spatial clusters, with the largest cluster extending from the central-eastern to eastern Java Sea. Kangean was located within this main DHW ≥4°C-weeks cluster, whereas Kepulauan Seribu and Karimunjawa were outside the main bleaching-level heat-stress cluster. This pattern indicated that the eastern Java Sea was the priority region for bleaching potential during the 2016 event. This result is consistent with the NOAA Coral Reef Watch concept, which considers spatially coherent DHW ≥4°C-weeks exposure as suggestive of an area of elevated bleaching risk rather than isolated short-term warming (Eakin *et al*., 2010; Heron *et al*., 2016; Liu *et al*., 2018). However, since this study is based on satellite-derived thermal stress metrics rather than on in situ observations of bleaching, the results should be regarded as the potential for bleaching, rather than as actual proof of witnessed coral bleaching. The reason this distinction is essential is that actual bleaching is also dependent on local reef conditions, coral community composition, water clarity, circulation, and historical thermal history (Baker *et al*., 2008; Fordyce *et al*., 2019; Skirving *et al*., 2020).

Figure 9 shows daily changes in SST, MHW categories, and DHW at three major coral reef sites in the Java Sea during 2016. Although all three sites experienced multiple MHW episodes, the degree of heat stress associated with coral bleaching differed significantly between sites. The Kepulauan Seribu experienced multiple MHW events, but the maximum DHW value only reached 0.44°C-week, well below the Alert Level 1 threshold (Figure 9a). Karimunjawa showed greater accumulation of heat stress, with a maximum DHW reaching 3.40°C-week, but still slightly below the 4°C-week threshold (Figure 9b). In contrast, Kangean showed the strongest heat stress among the three sites, with a maximum DHW reaching 4.87°C-week and exceeding the Alert Level 1 threshold (Figure 9c). Kangean also had the highest maximum HotSpot value and MHW intensity. Results suggest the 2016 extreme heat event did not affect coral ecosystem sites in the Java Sea in the same manner, with the eastern Java Sea, exemplified by Kangean, showing the greatest bleaching potential and the Seribu Islands and Karimunjawa Islands exhibiting conditions below the Alert Level 1 threshold. These results demonstrate that the bleaching potential was more dependent on the accumulation of HotSpots relative to the MMM than the MHW event alone.

 ISSN: 2714-8726

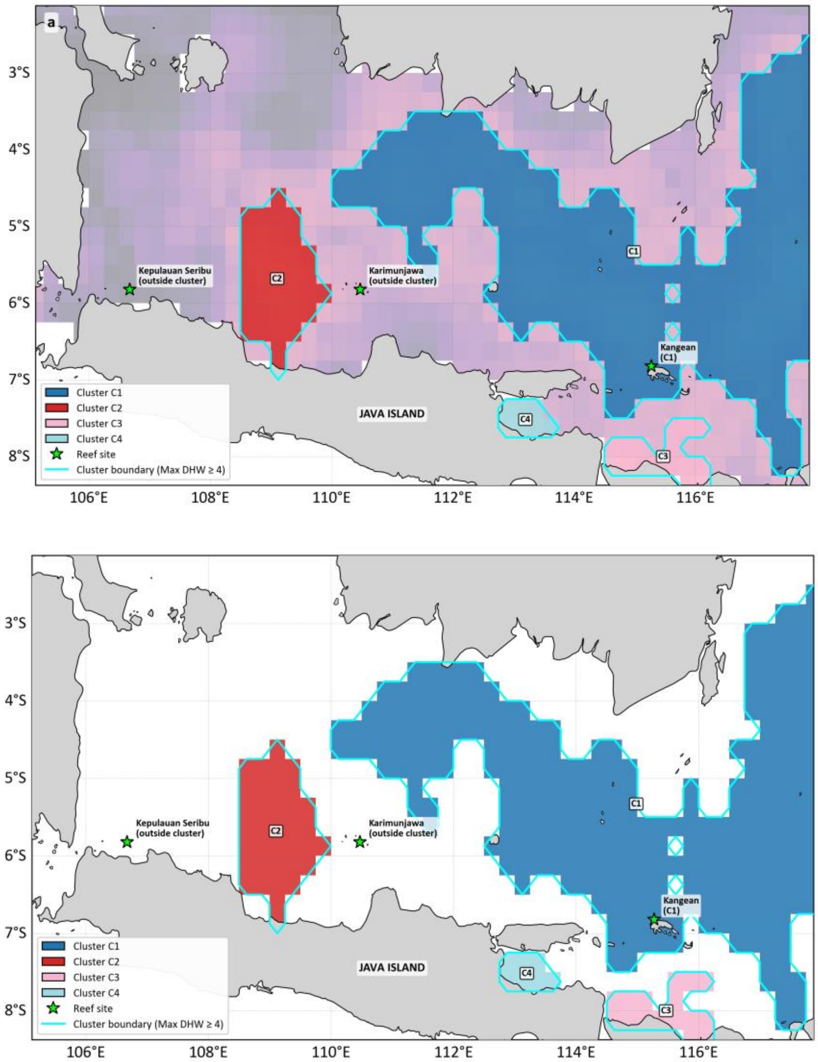

Figure 8. Spatial Hotspot Clusters of Bleaching-Level Heat Stress Max DHW ≥ 4 °C-weeks in the Java Sea (2016). Figure 8 shows the spatial clusters of priority bleaching-level heat stress areas in the Java Sea in 2016 (C1, C2, C3, and C4). The colored areas indicate grids that have achieved max DHW ≥ 4 °C-weeks, while the cyan lines indicate cluster boundaries. Green stars indicate the three reef-associated locations analyzed: Kepulauan Seribu, Karimunjawa, and Kangean. Clusters are formed from grids that meet the threshold of maximum DHW ≥ 4 °C-weeks.

The reef-site dashboard and the daily time series revealed substantial variations between the three reef-associated sites (Figures 10 and 9). Kepulauan Seribu had a long and cumulative MHW exposure, but with a maximum DHW of only 0.44°C-weeks. This shows that local MHW exposure did not aggregate to bleaching-level heat stress. The heat stress relevant for bleaching was higher in Karimunjawa and the maximum DHW was 3.40°C-weeks. This was nevertheless below the threshold for Alert Level 1. In contrast, Kangean reached a maximum DHW of 4.87°C-weeks, with DHW ≥4°C-weeks occurring for 53 days, suggesting persistent Alert Level 1 conditions.

These site-level results are in line with the geographic cluster analysis where Kangean was within the major DHW 4°C-weeks cluster. They also support the broader conclusion that exposure to MHW and the risk for bleaching were not uniform over the Java Sea. Kepulauan Seribu and Karimunjawa experienced MHW occurrences but failed to breach the Alert Level 1 threshold. Kangean accumulated HotSpots sufficient to breach the bleaching criterion. This is consistent with the NOAA Coral Reef Watch idea that DHW, rather than MHW duration alone, is the most direct indication of accumulated coral bleaching heat stress *(Heron et al.*, 2016; Liu *et al*., 2018; Skirving *et al*., 2020).

 ISSN: 2714-8726

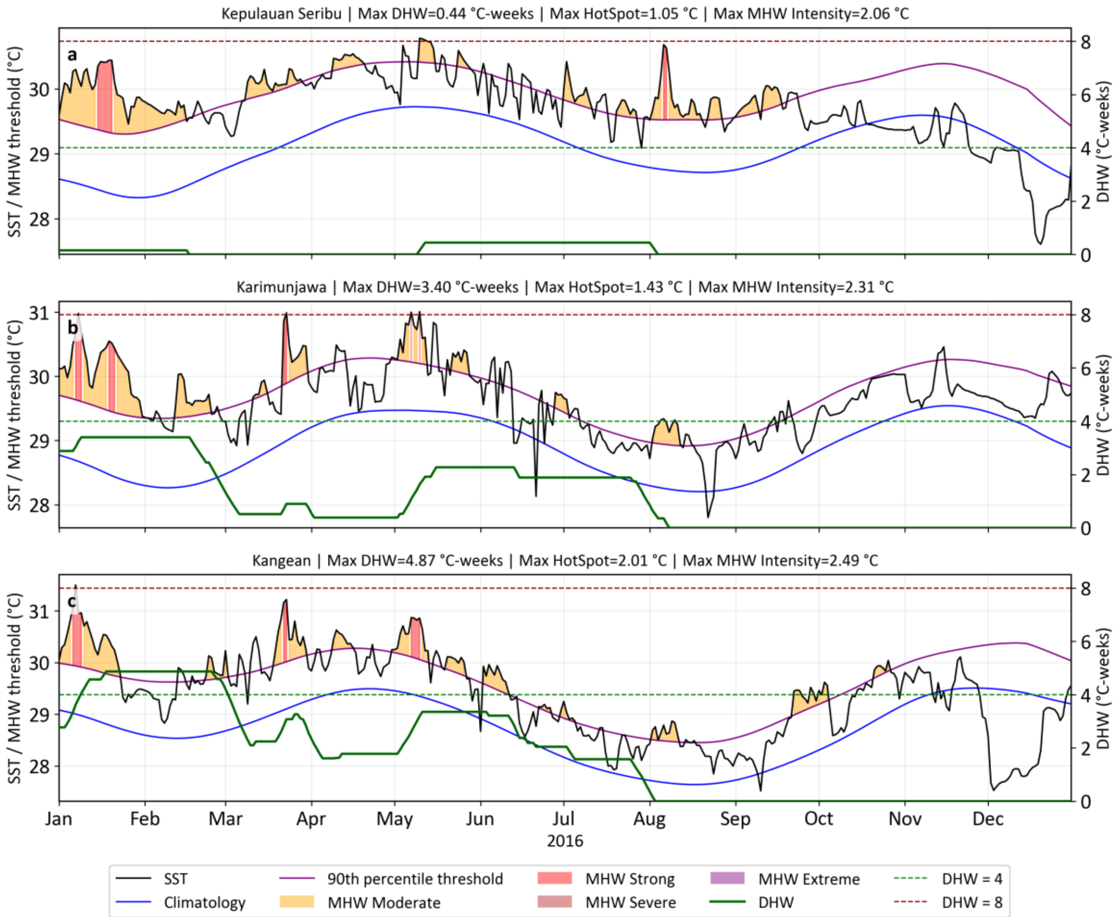

Figure 9. Daily SST, MHW Category, and DHW at Reef-Associated Sites in the Java Sea (2016). a. Kepulauan Seribu (Target coordinate: lat=-5.820, lon=106.670); b. Karimunjawa (Target coordinate: lat=-5.820, lon=110.470); c. Target coordinate: lat=-6.820, lon=115.270). This figure shows the daily evolution of SST, climatology, MHW threshold, MHW category, and DHW at three reef-associated sites in the Java Sea during 2016.

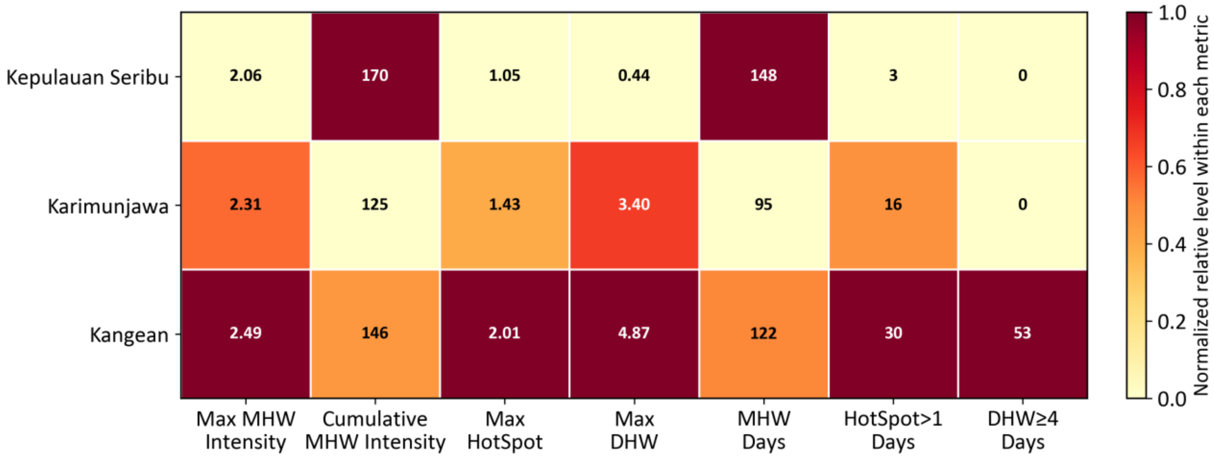

Figure 10. Reef-Site Dashboard: MHW Exposure and Bleaching Heat-Stress Metrics in the Java Sea (2016). The colors in each column are normalized relative to the locations for the same metric, while the numbers in the cells are the original values. Thus, a dark red color indicates that the location has the highest value for that metric compared to the other two locations, not necessarily in the same units as the other columns.

Results from the Java Sea demonstrate a more selective pattern compared to studies demonstrating widespread and severe bleaching during the 2015-2016 global bleaching event. This is similar to the broader background of thermal stress in 2016 reported by Hughes *et al.* (2017, 2018), Lough *et al*. (2018), and Setiawan *et al.* (2017), the level of severity is different in this study, as Alert Level 2 did not occur. The Java Sea in 2016, therefore, seems to have undergone localised to regional Alert Level 1 bleaching potential, with Kangean being the most exposed of the three reef-associated sites.

CONCLUSION

The 2016 thermal event in the Java Sea occurred with a widespread marine heatwave, however bleaching danger was not evenly distributed. MHW conditions were seen throughout much of the Java Sea, but bleaching-level heat stress was limited to areas where warm conditions surpassed the HotSpot threshold and lasted long enough to build up DHW. The maximum bleaching potential was seen in the eastern Java Sea, especially around Kangean. This area had reached Alert Level 1, whereas Kepulauan Seribu and Karimunjawa were below the threshold for Alert Level 1. Thus, whereas the 2016 event did not result in significant basin-wide bleaching-level heat stress, it did result in localised bleaching potential in reef-associated locations. Such data suggest that MHW incidence alone is not enough to be indicative of coral bleaching potential. HotSpot and DHW give a more meaningful assessment of heat stress as they are more relevant to coral bleaching. Therefore, a combination of MHW measures with HotSpot and DHW is valuable to identify reef areas in the Java Sea that should be more closely monitored during future significant warming occurrences.

ACKNOWLEDGEMENT

This research was funded by the National Research and Innovation Agency (BRIN), grant number: 38/II/HK/2022.

REFERENCES

Ampou, E. E., Johan, O., Menkes, C. E., Niño, F., Birol, F., Ouillon, S., & Andrefouet, S. 2017. Coral Mortality Induced by the 2015–2016 El Niño in Indonesia: The Effect of Rapid Sea Level Fall. *Biogeosciences*, 14(4): 817–826. https://doi.org/10.5194/bg-14-817-2017

Baker, A. C., Glynn, P. W., & Riegl, B. 2008. Climate Change and Coral Reef Bleaching: An Ecological Assessment of Long-Term Impacts, Recovery Trends and Future Outlook. *Estuarine, Coastal and Shelf Science*, 80(4): 435–471. https://doi.org/10.1016/j.ecss.2008.09.003

Burke, L., Selig, E., & Spalding, M. 2002. Reefs at Risk in Southeast Asia. World Resources Institute.

Burke, L., Reytar, K., Spalding, M., & Perry, A. 2011. Reefs at Risk Revisited. World Resources Institute.

Dias, M., Ferreira, A., Gouveia, R., Cereja, R., & Vinagre, C. 2018. Mortality, Growth and Regeneration Following Fragmentation of Reef-Forming Corals under Thermal Stress. *Journal of Sea Research*, 141: 71–82. https://doi.org/10.1016/j.seares.2018.08.008

Eakin, C. M., Morgan, J. A., Heron, S. F., Smith, T. B., Liu, G., Alvarez-Filip, L., Baca, B., Bartels, E., Bastidas, C., Bouchon, C., Brandt, M., Bruckner, A. W., Bunkley-Williams, L., Cameron, A., Causey, B. D., Chiappone, M., Christensen, T. R. L., Crabbe, M. J. C., Day, O., … Yusuf, Y. 2010. Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. *PLoS ONE*, 5(11). https://doi.org/10.1371/journal.pone.0013969

Edinger, E. N., Kolasa, J., & Risk, M. J. 2000. Biogeographic Variation in Coral Species Diversity on Coral Reefs in Three Regions of Indonesia. *Diversity and Distributions*, 6(3): 113–127. https://doi.org/10.1046/j.1472-4642.2000.00076.x

Fordyce, A. J., Ainsworth, T. D., Heron, S. F., & Leggat, W. 2019. Marine Heatwave Hotspots in Coral Reef Environments: Physical Drivers, Ecophysiological Outcomes and Impact upon Structural Complexity. *Frontiers in Marine Science*, 6: 466673. https://doi.org/10.3389/fmars.2019.00498

Genevier, L. G. C., Jamil, T., Raitsos, D. E., Krokos, G., & Hoteit, I. 2019. Marine Heatwaves Reveal Coral Reef Zones Susceptible to Bleaching in the Red Sea. *Global Change Biology*, 25(7): 2338–2351. https://doi.org/10.1111/gcb.14652

Gusviga, B. H., Subiyanto, Faizal, I., Yusri, S., Sari, S. K., & Purba, N. P. 2021. Occurrence and Prediction of Coral Bleaching Based on Ocean Surface Temperature Anomalies and Global Warming in Indonesian Waters. *IOP Conference Series: Earth and Environmental Science*, 750(1). https://doi.org/10.1088/1755-1315/750/1/012032

Heron, S. F., Maynard, J. A., Van Hooidonk, R., & Eakin, C. M. 2016. Warming Trends and Bleaching Stress of the World's Coral Reefs 1985–2012. *Scientific Reports*, 6: 1–14. https://doi.org/10.1038/srep38402

Hidayat, S. A., Ayuningtias, A., Cahyaningrum, Y. M., Astrida, N., & Kusumo, S. 2023. Temporal Study of Coral Reef Health in Kepulauan Seribu Marine National Park. *IOP Conference Series: Earth and Environmental Science*, 1260(1). https://doi.org/10.1088/1755-1315/1260/1/012015

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Moore, P. J., Scannell, H. A., Sen Gupta, A., & Wernberg, T. 2016. A Hierarchical Approach to Defining Marine Heatwaves. *Progress in Oceanography*, 141: 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

Hobday, A. J., Oliver, E. C. J., Sen Gupta, A., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Holbrook, N. J., Moore, P. J., Thomsen, M. S., Wernberg, T., & Smale, D. A. 2018. Categorizing and Naming Marine Heatwaves. *Oceanography*, 31(2): 162–173.

Hu, S., & Sprintall, J. 2017. Observed Strengthening of Interbasin Exchange via the Indonesian Seas Due to Rainfall Intensification. *Geophysical Research Letters*, 44(3): 1448–1456. https://doi.org/10.1002/2016GL072494

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., Smith, T., & Zhang, H. M. 2021. Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Journal of Climate*, 34(8): 2923–2939. https://doi.org/10.1175/JCLI-D-20-0166.1

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., … Wilson, S. K. 2017. Global Warming and Recurrent Mass Bleaching of Corals. *Nature*, 543(7645): 373–377. https://doi.org/10.1038/nature21707

Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., Baird, A. H., Baum, J. K., Berumen, M. L., Bridge, T. C., Claar, D. C., Eakin, C. M., Gilmour, J. P., Graham, N. A. J., Harrison, H., Hobbs, J.-P. A., Hoey, A. S., Hoogenboom, M., Lowe, R. J., … Wilson, S. K. 2018. Spatial and Temporal Patterns of Mass Bleaching of Corals in the Anthropocene. *Science*, 359(6371): 80–83. https://doi.org/10.1126/science.aan8048

IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC. 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844 (teks sumber mencampur label "AR4" dengan tahun 2022; judul disusun ulang mengikuti DOI, cek ulang)

Iskandar, M. R., Ismail, M. F. A., Arifin, T., & Chandra, H. 2021. Marine Heatwaves of Sea Surface Temperature off South Java. *Heliyon*, 7(12): e08618. https://doi.org/10.1016/j.heliyon.2021.e08618

Johnston, E. C., Counsell, C. W. W., Sale, T. L., Burgess, S. C., & Toonen, R. J. 2020. The Legacy of Stress: Coral Bleaching Impacts Reproduction Years Later. *Functional Ecology*, 34(11): 2315–2325. https://doi.org/10.1111/1365-2435.13653

Lachs, L., Bythell, J. C., East, H. K., Edwards, A. J., Mumby, P. J., Skirving, W. J., Spady, B. L., & Guest, J. R. 2021. Fine-Tuning Heat Stress Algorithms to Optimise Global Predictions of Mass Coral Bleaching. *Remote Sensing*, 13(14). https://doi.org/10.3390/rs13142677

Laufkötter, C., Zscheischler, J., & Frölicher, T. L. 2020. High-Impact Marine Heatwaves Attributable to Human-Induced Global Warming. *Science*, 369(6511): 1621–1625. https://doi.org/10.1126/science.aba0690

Leinbach, S. E., Speare, K. E., Rossin, A. M., Holstein, D. M., & Strader, M. E. 2021. Energetic and Reproductive Costs of Coral Recovery in Divergent Bleaching Responses. *Scientific Reports*, 11(1): 1–10. https://doi.org/10.1038/s41598-021-02807-w

Liu, G., Eakin, C. M., Chen, M., Kumar, A., De La Cour, J. L., Heron, S. F., Geiger, E. F., Skirving, W. J., Tirak, K. V., & Strong, A. E. 2018. Predicting Heat Stress to Inform Reef Management: NOAA Coral Reef Watch's 4-Month Coral Bleaching Outlook. *Frontiers in Marine Science*, 5: 1–23. https://doi.org/10.3389/fmars.2018.00057

Lough, J. M., Anderson, K. D., & Hughes, T. P. 2018. Increasing Thermal Stress for Tropical Coral Reefs: 1871–2017. *Scientific Reports*, 8(1): 1–8. https://doi.org/10.1038/s41598-018-24530-9

Muller, E. M., Bartels, E., & Baums, I. B. 2018. Bleaching Causes Loss of Disease Resistance within the Threatened Coral Species *Acropora cervicornis*. *eLife*, 7: 1–20. https://doi.org/10.7554/eLife.35066

Munasik, Sabdono, A., Benjamin, P. M., Haryanti, D., Wirasatriya, A., & Yusidarta, I. 2025. Rapid Assessment of Coral Bleaching Induced by 2023 ENSO in Karimunjawa, Central Java. *IOP Conference Series: Earth and Environmental Science*, 1496(1). https://doi.org/10.1088/1755-1315/1496/1/012029

Nugraha, W. A., Hidayah, Z., & Insafitri. 2013. Developing Coral Reef Conservation Zones in the Kangean Archipelago, Indonesia. Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA).

Oliver, E. C. J., Burrows, M. T., Donat, M. G., Sen Gupta, A., Alexander, L. V., Perkins-Kirkpatrick, S. E., Benthuysen, J. A., Hobday, A. J., Holbrook, N. J., Moore, P. J., Thomsen, M. S., Wernberg, T., & Smale, D. A. 2019. Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science*, 6: 1–12. https://doi.org/10.3389/fmars.2019.00734

Pujol, C., Pérez-Santos, I., Barth, A., & Alvera-Azcárate, A. 2022. Marine Heatwaves Offshore Central and South Chile: Understanding Forcing Mechanisms during the Years 2016–2017. *Frontiers in Marine Science*, 9: 1–20. https://doi.org/10.3389/fmars.2022.800325

Purwanto. 2003. Status and Management of the Java Sea Fisheries. In *Management and Future Directions for Coastal Fisheries in Asian Countries* (pp. 793–832).

Rachmayani, R., Ningsih, N. S., Hanifah, F., & Nabilla, Y. 2023. Long-Term Trend and Variability of Volume Transport and Advective Heat Flux through the Boundaries of the Java Sea Based on a Global Ocean Circulation Model (1950–2013). *Water (Switzerland)*, 15(4). https://doi.org/10.3390/w15040740

Schlegel, R. W., Oliver, E. C. J., Wernberg, T., & Smit, A. J. 2017. Nearshore and Offshore Co-Occurrence of Marine Heatwaves and Cold-Spells. *Progress in Oceanography*, 151: 189–205. https://doi.org/10.1016/j.pocean.2017.01.004

Schlegel, R. W., Smit, A. J., Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J., Benthuysen, J. A., Sen Gupta, A., Bindoff, N. L., Holbrook, N. J., Mundy, C. N., & Perkins-Kirkpatrick, S. E. 2018. heatwaveR: A Central Algorithm for the Detection of Heatwaves and Cold-Spells. *Journal of Open Source Software*, 3(27): 821. https://doi.org/10.21105/joss.00821 (

Setiawan, F., Muttaqin, A., Tarigan, S. A., Sabil, A., & Pinkan, J. 2017. Coral Bleaching Due to Global Warming in 2016 on Coral Reef Ecosystems: A Case Study in the Gili Matra Reserve (Gili Air, Gili Meno, and Gili Trawangan) Province of NTB. *Journal of Fisheries and Marine Science*, 1(2): 39–54. http://jfmr.ub.ac.id

Skirving, W., Enríquez, S., Hedley, J. D., Dove, S., Eakin, C. M., Mason, R. A. B., De La Cour, J. L., Liu, G., Hoegh-Guldberg, O., Strong, A. E., Mumby, P. J., & Iglesias-Prieto, R. 2018. Remote Sensing of Coral Bleaching Using Temperature and Light: Progress towards an Operational Algorithm. *Remote Sensing*, 10(1). https://doi.org/10.3390/rs10010018

Skirving, W., Marsh, B., De La Cour, J., Liu, G., Harris, A., Maturi, E., Geiger, E., & Eakin, C. M. 2020. CoralTemp and the Coral Reef Watch Coral Bleaching Heat Stress Product Suite Version 3.1. *Remote Sensing*, 12(23): 1–10. https://doi.org/10.3390/rs12233856

Wijaya, A. S., Haryanti, D., Ramadhan, M. F., & Wijayanti, D. P. 2025. Abundance and Diversity of Coral Reef Megabenthos in Karimunjawa Islands, Central Java. *Jurnal Kelautan Tropis*, 28(1): 82–90. https://doi.org/10.14710/jkt.v28i1.24514

Wouthuyzen, S., Abrar, M., & Lorwens, J. 2018. A Comparison between the 2010 and 2016 El Niño Induced Coral Bleaching in the Indonesian Waters. *IOP Conference Series: Earth and Environmental Science*, 118(1). https://doi.org/10.1088/1755-1315/118/1/012051

Wulansari, W., Widada, S., Maslukah, L., Wirasatriya, A., & Sari, T. 2026. Coastal Marine Heatwaves Detection in Java Using Satellite and In Situ. *Buletin Oseanografi Marina*, 15(1): 45–55. https://doi.org/10.14710/buloma.v15i1.78458

Xu, T. F., Wei, Z. X., Susanto, R. D., Li, S. J., Wang, Y. G., Wang, Y., Xu, X. Q., Agustiadi, T., Trenggono, M., Sulistyo, B., Setiawan, A., Kuswardani, A., & Fang, G. H. 2021. Observed Water Exchange between the South China Sea and Java Sea through Karimata Strait. *Journal of Geophysical Research: Oceans*, 126(2): 1–25. https://doi.org/10.1029/2020JC016608