The potency of Sentinel-2 satellite for monitoring during and after coral bleaching events of 2016 in the some islands of Marine Recreation Park (TWP) of Pieh, West Sumatra

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Abstract. The coral bleaching event (CBE) which triggered by increase in sea temperatures of 1-2˚C during El-Nino can make corals stressful or potentially dead. Many CBE research are conducted using sea temperature data measured through infrared thermal (TIR) satellite sensor. However, very few study use optical remote sensing data. This study aim to analyze the potential of optical Sentinel-2 (S-2) satellite data for monitoring during (Jun. 2016) and after (Jun. 2018) CBE in small islands of marine protected areas (TWP) of Pieh. A series image analysis procedure was conducted, i.e. simple DOS atmospheric correction; normalizing digital numbers (DN) of Blue, Green and Red bands of subject images during and after CBE to the reference image (before CBE, Dec. 2015) using “pseudo invariant feature (PIF)” approach; subtracting the DN of each bands of images during and after CBE to the reference image, and generating color composite of natural color with a contrast stretch. Result showed that this procedure can detected clearly the CBE. There was an average decreasing bleaching trend of 1.63 ha (15.8%), which indicated that some corals have recovered from thermal stress inside the TWP of Pieh. However, islands outside the TWP of Pieh, showed an increasing trend by an average of 0.50 ha (21.2%). The predation corals by the crown of thorn seastar, Acanthaster planci, whose population exploded after CBE was the main reason why CBE still detected both inside and outside the TWP of Pieh. This study shows the ability and potency of optical remote sensing data of S-2 satellite to monitor CBE, but need a lot of validation from many other sites. This result is very useful for supporting project such as COREMAP CTI.

1. Introduction

Coral reef ecosystem is one of the ecosystem with very high productivity in coastal areas in addition to seagrass and mangroves [1]. It can produce goods and environment services, that support life and
prosperity for people living on the coastal zones and small islands in the tropics with contributions of US$ 30 billion, including the value from recreation, marine tourism, fisheries, coastal protection and biodiversity services [2, 3]. However, coral reef ecosystems in the world, have been degraded due to various disturbances of human activities (heavy sedimentation, pollution, bad fishing practices, over exploitation of reef resources), as well as natural disturbances (massive coral predation by thorn starfish, Acanthaster planci, coral diseases, and global warming that causes coral bleaching) [3].

The phenomenon of coral bleaching is the occurrence in which coral (Polyps) release their symbionts, namely single-celled microscopic algae from the genus Symbiodinium known as zooxanthellae that lives on coral tissue. Thus, the variation color of corals turn white as the color of their skeleton [4-8]. This phenomenon is generally triggered by El Niño events, which cause the sea temperatures to rise by around 1-2°C or higher and heat a water body for 4-8 weeks or longer that making the coral stressful or potentially dead [9-17].

In the Indonesian waters, CBE have taken place at least 4 times, i.e. 1982/83, 1996/1997, 2010 and 2016 [18]. The last two events have been monitored and reviewed by [18, 19] using an effective and efficient techniques of remote sensing through the analysis of long-term sea surface temperature (SST) data of 2002-2018 that acquired from thermal infrared (TIR) sensor of Aqua MODIS satellite with spatial resolution of 4 km x 4 km. The SST products from various satellites are now become a standard tool for monitoring CBEs such as done by NOAA in their coral reef watch programs.

However, information on research/monitoring of CBE using optical data (visible wavelength) with high (< 10 m) or moderate resolution (≥ 10~30 m) of various satellites data in Indonesian waters is still very rarely to find, even though it has been pioneered since the early of 2000s. For example, [20], [21], [22] and [23] have been conducted study and/or monitoring of CBE using Landsat-5 TM (30 m) in the Ishigaki Island, Japan; IKONOS (4 m) in the Keppel Islands, Great Barrier Reef, Australia; IKONOS and QuickBird (2.4 m) in the Roatan Island, Honduras, Western Caribbean; and Sentinel-2 (10 m) in the Marquesas Islands, French Polynesia, respectively. This study aims to analyze the potential of optical sensor in S-2 satellite images to monitor before, during and after the 2016 strong CBE that occured in the small islands of Marine Protected Areas (TWP) of Pieh, Padang waters, West Sumatra Province.

2. Methodology

2.1. Study sites and times

The site of this study is one of national marine conservation area in Indonesia with its function as marine recreation park (TWP) of Pieh Island. This region at least had twice experienced CBE in 2010 and 2016 [18, 19]. Therefore, CBE needs to be continuously monitored and analyzed to determine the adaptability of corals (coral resilience) that live there due to the exposure of corals to high sea temperatures triggered by El Nino events, (during CBE) as well as after CBE.

The TWP of Pieh (99.80°~100.22°E; 0.75°~1.50°S) is situated in the administrative areas of Padang and Pariaman Cities, and Padang Pariaman District, West Sumatra province. It is determined by Decree of the Ministry of Marine and Fisheries Affair, No. KEP.70/MEN/2009, September 3, 2009. This area consisted of several small islands, namely Bando, Pieh, Air, Pandan, and Toran Islands, include several reefs with a total area

**Figure 1.** Map of the study sites, the TWP of Pieh which is bordered by the red lines.
of 39,900 ha (Figure 1). In addition, we expanded our observations into the islands outside (south) the TWP of Pieh, namely Sibuntar, Bindalang and Sinyaru Islands (Figure 1), which are not under the management of the TWP of Pieh.

Field surveys which related to the biological aspects of corals such as sea temperature, salinity, water transparency, sedimentation, dissolved Oxygen, pH, phosphate and nitrate were conducted at the end of June to the early of July 2018. Those parameters were also measured for a cluster islands of Kasiak, Angso Duo, Tangah and Ujuang which belonging to the Regional Marine Conservation Area (KKPD) of Pariaman City. The TWP of Pieh and its surrounding waters are strongly influenced by the water mass of Indian Ocean.

2.2. Sentinel-2 (S-2) satellite data

Launched on June 2015 and July 2016, the S-2a and S-2b satellites are the first optical earth observation satellites in the European Copernicus (new name of the European Commission's Earth observation) programme. S-2 Carries Multi-Spectral Imager (MSI) sensor, which covered 13 spectral bands (443–2190 nm), with a swath width of 290 km and a spatial resolution of 10 m with 4 visible and near-infrared/NIR bands (Table 1), resolution of 20 m with 6 red edge and shortwave infrared bands, and resolution of 60 m with 3 atmospheric correction bands. The geometric revisit time is 5 days from two-satellite constellation at equator [24].

With rapid revisit times, moderate spatial resolution, global coverage, and freely available data suggest the potential for time series analyses. It seems that S-2 may also be capable of coral bleaching detection [25]. Therefore, in this study we used 3 multi-temporal images of S-2, i.e. before CBE of December 31, 2015, during or at CBEs of June 08, 2016 and after CBE of June 28, 2018 (Figure 2). The S-2 satellite data can obtained and downloaded for free through the USGS Global Visualization Viewer web [26]. Figure 2 shows image at CBE was covered by clouds including Bando and Pieh Islands. Thus, analysis can be conducted for cloud-free Islands only.

Table 1. Spectral specification of four 10-m spatial resolution of S-2 satellite used in this study

| S-2 Bands | Central Wavelength (µm) | Bandwith (µm) |
|-----------|-------------------------|---------------|
| Band 2 (Blue) | 0.490 | 0.065 |
| Band 3 (Green) | 0.560 | 0.035 |
| Band 4 (Red) | 0.665 | 0.030 |
| Band 8 (NIR) | 0.842 | 0.115 |
In the analysis, we used 3 bands in the visible wavelength (Blue, Green and Red Bands) out of 4 available bands within the resolution of 10 m of S-2 satellite. The use of these 3 bands is due to the penetration ability ranging from 5 to 7.5 m in the Red band and 10 to > 25 m in the Blue-Green bands, especially in clear waters [27, 28, 29] such as in coral reef waters, so that the coral lies in various depth before, during, and after the bleaching event can be observed.

2.3. Data analysis

In assessing benthic habitats such as CBE, there are many phenomena that affect the visibility of satellite images, including sensor characteristics, atmospheric optical properties (including clouds), the level of sun glint of the sea surface, and the inherent optical properties of the water column [21]. Therefore, all of these influenced parameters must be corrected. Furthermore, because the object of this study (coral) lies below the sea surface, where radiation from such objects (water bodies, lake/sea) has a spectral response that is much weaker than the object on land [30] and experiences significant and strong interactions with the atmosphere before reaching the satellite sensor, then it is very important to apply atmospheric correction during pre-processing, especially for multi-spectral data of multi-temporal satellite images for monitoring purposes [31, 32].

Thus, the first step, we use a very simple atmospheric correction called Dark Object Subtraction (DOS). By doing this, it is assumed that the dynamics of changes in coral conditions, which interpreted from the results of satellite image processing are not due to atmospheric effects or other biases [33], so that changes in coral conditions before, during and after CBE are can be compared each other. This study follows a similar study of coral bleaching in the Honduras waters that uses 4 multi-temporal IKONOS images, which apply the DOS as a simple method to correct atmospheric effects [22]. Although this method is simple, it has proven effective in reducing the enormous atmospheric influences in analyzing satellite image data as stated by [34, 35, 36] from the results of their studies. However, other pre-image processing such as sun glint and water column corrections [23] are not applied in this study.

The second step, we used correction technique of pseudo invariant features (PIF) that originally developed by [37]. This technique is an empirical conversion based on the assumption of a linear relationship between image bands across time, for features that are spatially well defined and spectrally radiometrically stable [35]. To conduct PIF approach, we extracted atmospherically corrected digital values (DN) of pixel from bright man-made objects in satellite images, such as concrete, asphalt, and rooftops of two runways of the new (north) and the old (south) airports of Padang, while the dark object is deep reef flat (> 5 m) (Figure 3) [21, 35]. The PIF approach makes use of bright and dark pixel sets extracted from the reference images before CBE (Dec. 2015), and subject images during CBE (Jun. 2016) and after CBE (Jun. 2018) to define a gain and offset for normalizing the subject image to match the radiometry of the reference image. The bright and dark pixel sets were used as input into a linear regression that yielding a gain and offset for converting the Jun. 2016 and Jun. 2018 DN into accord with Dec. 2015 DN, and plus a regression coefficient ($R^2$) [21, 22]. Same as DOS, this simple PIF approach have been used effectively for a number change detection studies of the reefs [21, 22, 38, 39] as well as terrestrial applications [40]. However, in the next study, it is also need to applied water column correction [23] in order to achieve the best results.

The third step is to generate the spectral difference by subtracting the DN values of each band (Blue, Green and Red Bands) of Jun. 2016 image during CBE, and DN values of each band of Jun. 2018 after CBE by the DN of each band of the reference image of Dec. 2015 before CBE. The procedure at this step is based on the assumption that the DN values of image of healthy (living) corals before CBE (Dec. 2015) has lower DN than at CBE (Jun. 2016). Since living coral symbiosis with a single-cell micro algae genus Symbiodinium known as zooxanthellae that lives in coral tissues [9, 11, 13, 16, 41, 42], in which the chlorophyll-a pigment in zooxanthellae absorb the light energy [43].

On the other hand, during CBE, corals are in a stressful condition due to increase of high sea temperature; thus, corals expel their symbiont. As a consequence, the variation color of corals become white as the color of limestone, the skeleton of corals [4, 6, 12, 44]. Thus, during this condition, the
white color of coral’s skeleton reflect light with a stronger spectral approximately twice as brighter as healthy unbleached coral, which spectral reflectance of coral rising from about 10 to 20% when bleached [20, 45]. After CBE (Jun. 2018), the spectrals reflected by coral are expected to be slightly lower than during CBE, because corals might be die and then covered with macro algae or coral recovered again. This process will cause light energy exposed to coral to be absorbed by chlorophyll-a which both exists in the tissues of macro algae and zooxanthelae, respectively.

The final step is to combine the first 3 difference bands (Band 2, 3 and 4 as Red, Green, and Blue) during CBE and after CBE to form a color composite and by applying a contrast stretch, the location of the bleached coral could be readily discerned based on their bright gold tone [21, 22, 23]. However, in this study, we generate color composite as natural color (Band 2, 3 and 4 as BGR color gun) that produce a distinct of cyan color, which indicated corals bleached. Benthic areas with little or no change remain dark in the color composite [21].

3. Results and Discussion

The TWP of Piêh consists of very small islands (Bando, Piêh, Pandan, Air and Toran Islands), so that if the CBE is fully analyzed for the whole TWP areas (Figure 1), the results are not clearly visible. Therefore, in this study, the analysis was carried out separately for each island. There are 3 S-2 satellite images used, 2 of which are cloud-free, i.e. before (Dec. 2016) and after CBE (Jun. 2018). Unfortunately, during CBE of Jun. 2016 (Figure 4), the available S-2 image has a wide degree of cloud cover, where Bando and Piêh Islands are in the middle of cloud cover (Figure 2). Thus, only 3 islands can be analyzed, but outside the TWP of Piêh, 3 other islands (Bindalang, Sinyaru and Sibuntar Islands) are cloud-free, so we extended our analysis to these islands.

3.1. Coral status in the TWP of Piêh

In general, the coral reefs at the TWP of Piêh and surrounding waters are classified as fringing reefs and patch reefs. The distribution of small islands and series of coral reefs formed an elongated formation north-south along the main coastline (west Sumatra coast) with a distance of 25-30 km from the nearest coastline. The islands in these areas categorized as very small islands with an area ranging from 5-28 Ha. The island is uninhabited with white sandy beaches and covered with main vegetation of coconut, ketapang and waru laut [46].
Coral cover on this island varies greatly as shown in Table 2 [46]. It ranges from 7.6% to 72.1% with an overall mean of 34% inside the TWP of Pieh, but more lower for outside with an overall mean only of 14.8%. Corals in the TWP of Pieh are more dominated by non-Acropora types than Acropora types, both inside and outside of the TWP with percentage cover of 0.6 and 33.1%, respectively. From Non-acropora types, the main of benthic coral life forms are dominated by encrusting corals (CE) of 20.9%, followed by foliose corals (CF) of 5.6%, massive corals (CM) of 2.8%, branching corals of 2.1% and sub-massive corals (CSM) of 1.8%, other live forms < 1%, while the rest are non-living corals, such as dead coral, dead coral covered by algae, sand and other components. Those kind of coral life forms as described above bleached during CBE of Jun. 2018 as shown in Figure 4.

### Table 2. Percentage of coral covers and coral life forms in the Islands inside and outside the TWP of Pieh [46].

| Locations inside the TWP of Pieh | Latitude | Longitude | N | Coral Covers (%) | Benthic corals life form (%) |
|----------------------------------|----------|-----------|---|------------------|-----------------------------|
| Toran                            | -1.0409~ | 100.1690~100.17 | 80 | 4 | 7.6 | 72.1 | 2 | 0.6 | 35.6 | 4.1 | 17.9 | 0.8 | 1.9 | 10.5 |
| Pandan                           | -0.9702~ | 99.9986~100.138 | 6 | 5 | 28.4 | 36.7 | 6 | 0.6 | 35.3 | 0.3 | 20.2 | 4.8 | 3.1 | 7.6 |
| Pieh                             | -0.8763~ | 100.0976~100.10 | 23 | 5 | 13.2 | 44.4 | 2 | 0.6 | 31.6 | 0.5 | 19.6 | 2.0 | 0.7 | 8.9 |
| Bando                            | -0.7684~ | 99.9937~99.9983 | 4 | 4 | 29.3 | 57.9 | 2 | 0.9 | 38.3 | 5.2 | 27.2 | 3.2 | 2.4 | 0.4 |
| Air                              | -0.8774~0.8729 | 100.2044~100.20 | 51 | 4 | 19.6 | 33.4 | 7 | 0.6 | 24.9 | 0.6 | 19.6 | 3.5 | 0.6 | 0.6 |
| Overall Mean                     |          |            |   | 4 | 19.7 | 48.9 | 0 | 0.6 | 33.1 | 2.1 | 20.9 | 2.8 | 1.8 | 5.6 |

| Locations outside the TWP of Pieh | Latitude | Longitude | N | Coral Covers (%) | Benthic corals life form (%) |
|-----------------------------------|----------|-----------|---|------------------|-----------------------------|
| Sao                               | -0.86031 | 100.3032 | 1 | 7 | 4.9 | 14.7 | 4.9 | 10.9 | 1.8 | 1.5 |
| Sinyaru                           | -1.07275 | 100.2969 | 1 | 9.8 | 0.7 | 8.7 | 1.4 | 3.9 | 1.9 | 0.7 |
| Overall Mean                      |          |            |   | 8 | 2.8 | 11.7 | 3.2 | 7.4 | 1.7 | 0.1 | 0.1 |

Remarks: N=Number of transects, AC= Acropora types, NAC non-Acropora types, CB= Branching corals, CE= Encrusting Corals, CM= Massive corals, CSM= Sub-massive corals, CF= Foliose corals.

**Figure 4.** Severe CBE of Jun. 2016 in the Pieh Island. The sea temperature reaches 31°C at depth of 17 m.
3.2. Pseudo-invariant features (PIF) analysis

Figure 5 shows an example plot of the bright (airport) and the dark (deep reef flat) objects pixels (see figure 3) of the reference before CBE of Dec. 2015 and subject images at CBE of Jun. 2016, for Blue band that used in pseudo-invariant features (PIF) analysis. Further, the normalization calculation was performed to normalized the atmospheric corrected DN of each band of subject images during CBE of Jun. 2016 as well as after CBE of Jun. 2018. Gains and offsets (table 3) were then applied to the reference image before CBE of Dec. 2015.

Table 3. Normalization regression equations using (PIF) approach during CBE of Jun. 2016 and after the event Jun. 2018 against the DN values of reference image before CBE of Dec. 2015. (See figure 5)

| Date and spectral bands | Gain (a) | Offset (b) | R²       |
|-------------------------|----------|------------|----------|
| June 2016               |          |            |          |
| • Band-2 (Blue)         | 1.145    | -1.239     | 0.942    |
| • Band-3 (Green)        | 0.295    | -6.330     | 0.958    |
| • Band-4 (Red)          | 0.978    | -1.289     | 0.978    |
| • Band-8 (NIR)          | 0.988    | -25.684    | 0.991    |
| June 2018               |          |            |          |
| • Band-2 (Blue)         | 1.182    | -146.33    | 0.929    |
| • Band-3 (Green)        | 1.124    | -24.078    | 0.961    |
| • Band-4 (Red)          | 1.097    | -29.517    | 0.981    |
| • Band-8 (NIR)          | 1.027    | -11.637    | 0.993    |

Based on the normalized regression equation in table 3, the DN of each band from the normalized image at CBE of Jun. 2016 and after CBE of Jun. 2018 is subtracted by each of the same bands from the reference image before CBE of Dec. 2015 (eg. normalization Band-2 of Jun 2016 - (minus) DN band 2 of reference image of Dec. 2015, and so on). By generating a color composite using the first three image difference bands (Band-2, -3 and -4 as Red, Green and Blue (pseudo color), as well as Blue, Green and Red (natural color)) and by applying a contrast stretch, the location of the bleached coral could be readily discerned based on their bright gold tone [21, 23, 25] and sharp cyan color as shown in Figure 6. In this study we more prefer natural color composits. Figure 7 shows the results of coral bleaching mapping following band normalization (PIF) approach for Toran, Pandan and Air Islands.

Figure 6. Coral bleaching image at CBE (June 2016) in the Toran Island, TWP of Pieh produced using the PIF approach. A: Psuedo color composite (B-2, -3 and -4 as Red, Green and Blue), and B: Natural color composite (B-2, -3 and -4 as Blue, Green and Red).
Figure 7. Color composite images (Red = B-4, Green= B-3 and Blue=B-2) of S-2 satellite produced using PIF approach that showing the coral bleaching spots (white color) for the Toran, Pandan and Air Islands during CBE of Jun. 2016 (A, B and C) and after CBE of Jun. 2018 (A’, B’ and C’).

3.3. CBE Detection

The coral bleaching areas (ha) both at CBE (June 2016) and after CBE (June 2018) of figure 7 can be calculated. We also expanded the calculation to 3 cloud-free islands outside the TWP of Pieh using the PIF approach. The bleaching area for all of the islands observed is listed in table 4.

Inside the TWP of Pieh, Air Island has the smallest coral reef areas of around 13.3 ha and Toran Island has the largest of 76.1 ha, while the next sequences are Pandan, Bando and Pieh Islands with coral reef areas of 54.1, 39.3 and 38.3 ha, respectively. During Jun. 2016 CBE, Coral reefs of Toran

Table 4. The dynamics of coral bleaching on the islands located inside and outside the TWP of Pieh derived using S-2 satellite data by applying the PIF approach.

| Observed Island | Reef areas (ha) | Bleached Areas During CBE of June 2016 (ha) (%) | After CBE of June 2018 (ha) (%) | A Bleached areas during - after CBE (ha) (%) |
|-----------------|----------------|-----------------------------------------------|---------------------------------|---------------------------------------------|
| Inside the TWP of Pieh | | | | |
| • Bando Island | 39.3 | n/a | 0.6 | 2.0 | - |
| • Pieh Island | 28.1 | n/a | 1.1 | 3.9 | - |
| • Pandan Island | 54.1 | 5.8 | 10.7 | 3.2 | 5.9 |
| • Air Island | 13.3 | 0.9 | 6.8 | 1.2 | 9.0 |
| • Toran Island | 76.1 | 8.2 | 10.8 | 4.7 | 6.2 |
| Outside the TWP of Pieh | | | | |
| • Bindalang | 61.1 | 4.2 | 6.9 | 4.3 | 7.0 | +0.1 | +3.4 |
| • Sibuntar Island | 37.3 | 3.3 | 8.8 | 4.5 | 12.1 | +1.2 | +14.6 |
| • Sinyaru Island | 43.7 | 0.9 | 2.1 | 1.0 | 2.3 | +0.1 | +45.7 |

Note: n/a: No available data due to cloud cover at CBE of Jun. 2016 (see Figure 2); - (negative) denotes: coral bleaching areas were decreased, while + (positive) means bleaching areas were increased
experienced the largest bleaching of 8.2 ha, followed by the Pandan Islands 5.8 ha and Air Island as the lowest of only 0.9 ha. However, the percentage of coral-bleached areas on Toran and Pandan reefs are almost the same of 10.7%, while 6.8% in Air Island. The coral bleaching areas in Bando and Pieh Islands cannot be assessed because the area is covered in thick clouds.

After CBE, we got and used a free-cloud S-2 satellite image of June 03, 2018. We still detected bleached corals. From the total coral reef areas of Bando and Pieh Islands, bleached coral are detected about 0.6 ha (2%) and 1.1 (3.9%), respectively. However, we did not know the bleaching condition during CBE of June 2016. In the Toran and Pandan Islands, although there was a decreasing trend of 4.7 ha (6.2%) and of 3.2 ha (5.9%), bleached corals are still detected, except for Air Island that showed an increasing of 1.2 ha (9.0%). Thus, the overall of bleached coral areas during CBE of June 2016 and after CBE of June 2018 decreased about 3.5 ha (42.9%) and 2.6 ha (39.3%) for Toran and Pandan reefs, respectively, but increased of 0.3 ha (34.9%) for the reefs in the Air Island.

Outside the TWP of Pieh, we also analyzed the coral bleaching in 3 Islands of Bindalang, Sibuntar and Sinyaru Islands (Table 4). Bindalang Island is the widest Island (61.1 ha) followed by Sibuntar (43.7 ha) and Sinyaru Islands (37.3 ha). During CBE of June 2016, we detected about 4.2 ha (6.9%), 3.3 ha (8.8%) and 0.9 ha (2.1%) of bleached coral reefs on Bindalang, Sibuntar and Sinyaru Islands, respectively. After the CBE of June 2018, it was surprising to find that there was an increase in coral bleaching for the all three observed Islands. Between the period of time during CBE of June 2016 and after the CBE of June 2018, there was an increase in coral bleaching areas, although not too large, i.e. 0.1 ha (3.5%), 1.5 ha (14.6%) and 0.1 ha (45.7%).

3.4 Observation SST before, during and after CBE

As suggested by [33] that in CBE observations, continuous monitoring of SST needs to be done to determine the stress level of coral. Figure 8 shows distribution map of degree heating weeks (DHW, °C-Week) generated from thermal infrared (TIR) data of Aqua-MODIS satellite before, during and after CBE. This map can be used to know the severity of corals exposed to high sea temperature.

Before CBE (Dec. 2015), DHW map of ≤ 0 spread evenly in almost all study sites. This means that corals did not experienced thermal stress due to the high sea temperature [13, 18]. On the other hand, during CBE (Jun. 2016) all study sites were covered by the distribution DHW of 4-8 (Alert-1), which meant that coral reefs were under thermal stress due to the high temperatures and caused corals to bleach partially [13, 18] (Figure 4). After CBE (Jun 2018), the sea temperature measured in the field ranging from 29.1 to 30.0 °C with an average of 29.5 °C [47]. This value is lower than the maximum mean monthly sea temperature value (MMM), which is the maximum value of the long-term average SST (> 7 years) that can be tolerated by corals [13,18]. The MMM value for Indonesian waters is 29.2 °C, while for waters around TWP of Pieh is 29.6 °C [48]. Therefore, after CBE, sea temperatures

![Figure 8. DHW map generated using TIR data of Aqua MODIS before, during and after CBE in the study areas.](image-url)
are returns to normal such as before CBE, which means that corals are actually free from thermal stress. Although the CBE has been over for two years, but bleached corals are still detected, and even in some islands the bleaching areas increased (figure 7; table 4).

Detection of the bleached areas after CBE of Jun. 2018 is not due to increase of SST as explained above, but because of the predation of corals by crown of thorn seastar, *Acanthaster planci*, whose population exploded in huge numbers during 2017 (figure 9). The predation of these animals on coral cause permanent coral damages, due to the corals (polyps) die completely, so the remains are the white skeletons of coral. This is different from coral bleaching due to the rising sea temperatures. At the level of Alert-1 (figure 8) coral can still survive and recover. Figure 10 shows the recovery of coral from CBE in 2010, which can be seen from the increase of percentage of living coral cover. Strong CBE again occurred in 2016, which caused the percentage of living coral covers to drop dramatically, but slowly coral recover again. This prove that corals can recover themselves, as also detected from the results of the S-2 satellite image analysis in this study (figure 7; table 4).

**Figure 9.** Double impacts of CBE in the TWP of Pieh due to high SST and predation of crown of thorn seastar, *Acanthaster planci* in Pieh Island (above) and Toran Island (bellow).

**Figure 10.** Coral recovery in the TWP of Pieh after twice exposed to CBE in 2010 and 2016 [34].

### 4. Concluding Remarks

In this study, CBE detection based on optical satellite image data follows the method of [21] using a PIF approach, which normalizes the DN of satellite images at the time of CBE of Jun. 2016 and after CBE of Jun. 2018 on the reference image before CBE of Dec. 2015 has yielded satisfactory results, even
though we used medium-resolution of S-2 satellite imagery (10 m) and by applying simple atmospheric correction of DOS. However, this method need a lot of validation from other different geographical areas and reef regimes [23] of Indonesian. Furthermore, a better atmosphere correction needs to be applied, such as Fast Line-of-Site Atmospheric Analysis of Spectral Hypercubes (FLAASH) [22] or other atmospheric correction methods. Some other corrections during image pre-processing are also need to be done such as sun glint correction (deglint) [23, 49], followed by water colour correction (depth invariant indichies) [23]. However, It should be noted too that the inappropriate selection of the method can cause overcorrection [50] to the original DN values of the image, so that the interpretation results might be become not so accurate.

Our results conclude that S-2 satellites with medium (10 m) spatial resolution combined with SST data analysis using Aqua MODIS satellite images and the availability of field data that we have contributed to a good result in monitoring CBE in the TWP of Pih. This is in line with CBE monitoring requirements suggested by [45] such as: 1). The use of high spatial resolution images (sub-meters will be optimal) in several visible wavelengths; 2). Continuous monitoring of SST to measure heat pressure on corals; 3). Inventory of coral reef systems and basic health; 4). Validation data to develop and improve bleaching detection methodologies and 5). Sophisticated image processing software and infrastructure.

Coral bleaching can be a short-lived phenomenon, with a spatial distribution scale that can vary greatly. Monitoring at the time of CBE urgently needs satellites that have short visit times, global coverage in tropical and/or sub-tropical waters of the world [51], and freely available data. In connection with the above objectives, the pairs of S-2A and S-2B satellites indicate their potential that meets the requirements for conducting CBE time series analysis compared to other satellites such as SPOT-4 and Landsat series satellites [25]. During the strong CBE 2016, at least 15 provinces with 20 regions in Indonesia were affected, including neighboring countries (Singapore, Malaysia, Brunei and Timor Leste) [19, 48]. Therefore, there are many opportunities to assess the condition of coral reefs before, during and after CBE in Indonesian waters while verifying/validating the results of this study.

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