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Detecting coral bleaching, using QuickBird multi-temporal data: A feasibility study at Kish Island, the Persian Gulf

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ABSTRACT

Coral bleaching events have become more frequent and intense worldwide and speculated to be a severe threat for coral survival in future. The Persian Gulf, as one of the warmest seas, has also experienced coral mortalities and bleaching events. Historically, bleaching events are known to occur south of the Persian Gulf, such information is scarce in the northern side. Perhaps remoteness and inaccessibility to Iran main coral communities which have developed on offshore islands can explain such lack of data. To address this issue, the feasibility of using multi-temporal satellite images for detecting past bleaching events were investigated. Two QuickBird images (2005, 2008) were selected to detect 2007 bleaching event at Kish Island, Iran, and the accuracy of results were compared to in situ observations. Current study might represent "algae-challenged" scenario in terms of having 7 months' time lapse between bleaching event and post-bleaching satellite image. As a result of this, we had algae-covered corals instead of white bleached corals. In the proposed procedure pre and post-bleaching images were classified, and changes in reflectance values within coral classes were interpreted as bleaching areas. By using this method we could eliminate the effect of miss-classification between bleached corals and sand; as well as algae-covered corals and live corals. Furthermore, it is not necessary to have a post-bleaching image acquired during bleaching events, although having such image will increase the accuracy. The proposed technique detected ~28% of bleached corals and the results support the idea that coral bleaching can be distinguished by detecting the changes in reflectance values in pre and post-bleaching images. Understanding the occurrence, severity, and extent of past bleaching events may help us understand the population dynamics of Iran corals and reveal coral connectivity patterns in the Persian Gulf.

1. Introduction

Coral reefs are under degradation due to anthropogenic stress and natural disturbances worldwide (Wilkinson, 2008). As a result of temperature rise in the world oceans, the frequency and the scale of bleaching occurrences have increased since the early 1980s (Glynn, 1993; Hoegh-Guldberg, 1999; Hoegh-Guldberg et al., 2007; Baker et al., 2008). Climate change scenarios suggest an increase in tropical ocean temperature (IPCC, 2007), potentially increasing bleaching events and killing many coral reefs around the world.

The Persian Gulf is known as the warmest sea in the world with high environmental fluctuations and temperature, well above the thermal tolerance for corals elsewhere (Wilkinson and Buddemeier, 1994; Sheppard et al., 2010; Riegl et al., 2011). Although, the Persian Gulf corals and their algal symbionts acclimatized and adapted to elevated temperatures (Baker et al., 2004; Obura, 2009), they could not escape temperature anomalies and have experienced bleaching events and mass mortalities (Coles and Fadlallah, 1991; George and John, 1999, 2000; Riegl, 2002, 2003; Riegl et al., 2011). Bleaching is the loss of coral symbiotic algae in response to environmental stresses (Hoegh-Guldberg et al., 2007; van Oppen and Lough, 2009). In particular, temperature anomalies (Berkelmans and Willis, 1999) will be a severe threat to coral survival for the next 30–50 years (Baker et al., 2008). Corals are not likely to withstand and recover from these events unless they acquire at least 0.2–0.3 °C thermal tolerance per decade (Donner et al., 2005). The Persian Gulf corals already cope with temperatures projected for corals elsewhere in future (Riegl et al., 2011). These corals are close

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to their tipping point, and further bleaching and mass mortalities will be inevitable in future. The Persian Gulf corals can serve as a good case study to investigate bleaching as well as implementing and testing different techniques to assess such events.

The Iranian coastline of the Persian Gulf is over 1300 km long, and main coral communities are located around offshore islands. Access to most of these areas is difficult, and establishing regular monitoring programs has not been successful so far. One of the current problems of coral studies in Iran is insufficient historical data on corals, their environments, and disturbances in particular bleaching events. This explains why few bleaching reports are available from the northern Persian Gulf compare with the south, where such data have been collected since 80's (Baker et al., 2008). Although, historical surface temperature anomalies can be acquired from satellite data, not all anomalies lead to bleaching. While in situ bleaching assessment is impossible, remote sensing techniques might be beneficial. Remote sensing has proved to be a useful tool for assessing impacts of environmental factors, ecological and geomorphological changes on coral reef communities (Palandro et al., 2003; Andréfouët and Riegl, 2004; Mumby et al., 2004); depth estimation (Lyzenga, 1978; Stumpf et al., 2003; Mishra et al., 2004), habitat mapping (Mumby et al., 1998; Andréfouët et al., 2003; Purkis and Pasterkamp, 2004; Green et al., 2005; Mishra et al., 2006); and bleaching detection across coral communities (Clark et al., 2000; Elvidge et al., 2004; Rowlands et al., 2008). The latter, needs high spatial resolution sensors (Andréfouët et al., 2002), and also using multi-temporal images can improve the accuracy of bleaching detection (Yamano and Tamura, 2004), especially when suitable satellite image is not available at the time of bleaching incident. Change detection and multi-temporal approach has been popular in land-based surveys and used in marine realms to detect coastline changes, estimation of reef topography, and changes in habitats (Yamano, 2007; Scopélitis et al., 2009; Lyons et al., 2011; Al Fugura et al., 2011). Elvidge et al. (2004) provided satisfactory account of multi-temporal images using pseudo-invariant features (PIF) and differential imaging (DI) based approach to detect coral bleaching in the Great Barrier Reef. Rowlands et al. (2008) used similar approach based on spectral radiance for detecting bleaching in Honduras and showed by having adequate habitat knowledge; this method can be valuable for detecting bleaching. Therefore, the multi-temporal approach might be beneficial in detecting past bleaching events and may be a cost-effective tool to assist future in situ observations and monitoring plans along the Iranian coastline. The current study is one of the first attempts to use multi-temporal images to detect bleaching and to assess its application for acquiring information of the past bleaching events in Iran, and in the Persian Gulf.

Here, we tested the potential and feasibility of using multi-temporal high resolution QuickBird imagery as a source of reference information on presence/absence, frequency, severity, and extent of coral bleaching events. We also examined the potential value and accuracy of such technique to acquire bleaching historical data, especially when there are no field observations available. Finally, we discussed the implications of this study for coral monitoring and management in remote places along Iranian coastline.

2. Materials and methods

2.1. Study area

The investigated area is a shallow subtidal sea bed, sloping gently offshore (~2%) to depth of ~10 m on the southeast side of the Kish Island. The island is a salt diapir and part of the southern Zagros Mountains, with fossil corals dating from the Holocene and upper Pleistocene geological periods (Preusser et al., 2003). It is located at northern side of the Persian Gulf (26° 32′ N; 53° 58′ E), about 17 km far from Iran mainland, with 90 km^2 area (Fig. 1). The tidal regime of the area is mixed, with a range of 1.8 m above the lowest astronomical tide datum. Water temperature usually ranges from 22 to 33 °C. Climate is very dry semi-equatorial with ~60% humidity, and air temperature ranges from 15 to 48 °C. The average annual rainfall is ~150 mm, which usually occurs during winter and fall. The site is one of the main diving destinations and therefore receives high anthropogenic impacts. Corals can be found all around the island on hard grounds, however, most developed and dense corals were located at southeast of the island, hence it was chosen as our study area (Fig. 1).

2.2. Field observations and in situ data collection

The distribution and community structure of corals in the study area has been under investigation since 2005 (Samimi-Namin, unpublished data). Only parts of the available data sets were used as training data to improve and verify the results. Corals extend parallel to shoreline in a belt between 2 and 12 m depth (Fig. 1), with variable density, diversity, and surface cover. The area was composed of three main coral assemblages, currently under study:

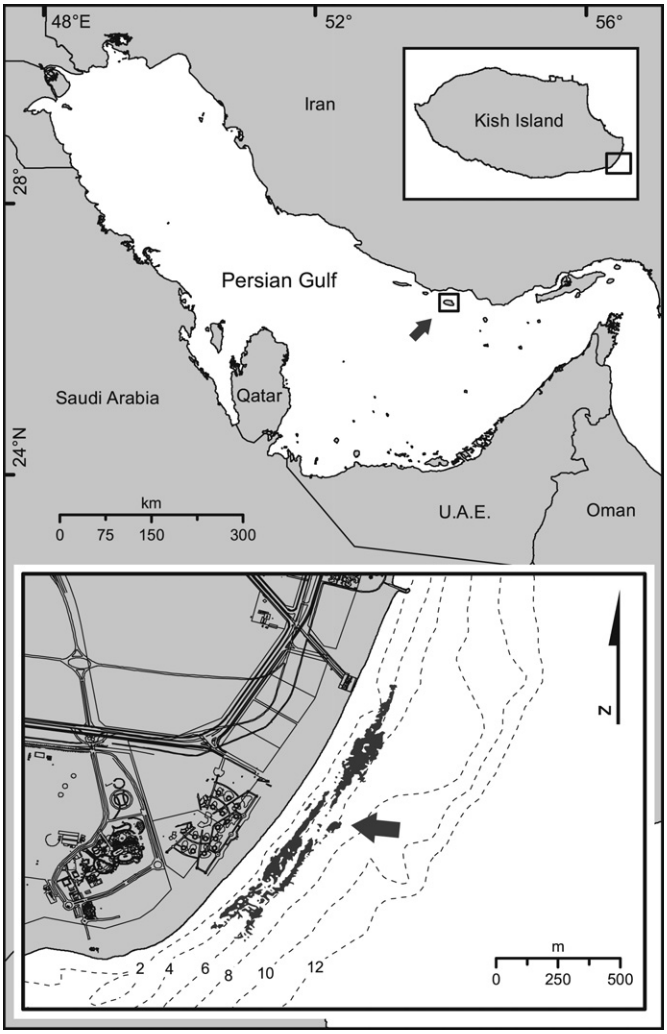

Fig. 1. Study area at SE of Kish Island, Iran, representing coral communities along the shoreline.

type a, massive dead or alive *Porites* colonies with, 10–30% cover; type b, non-frame-building *Acropora* colonies, with 40–80% cover; and type c, mixture of Poritids, Faviids, and Siderastreids in deeper areas, with 10–30% cover. It is not known whether the area represents true framework building corals and perhaps can be best classified as non-frame-building coral communities sensu Riegl and Piller (1999). For the purpose of the study we consider the mean coral cover of about 50% for the whole coral area.

The bleaching occurred at the study site from 10 to 28 August 2007 (Wilkinson, 2008) with ~85% (84.9 ± 6.3) of total coral colonies being partially or completely bleached during the first two weeks of the incident. During the first few days of bleaching, most of the *Acropora* colonies were bleached while other corals such as Faviids and Poritids, managed to survive. Two weeks later, all *Acropora* colonies were bleached, and even the other persistent genera could not escape the bleaching. Six months later, the coral skeletons were covered by algae and were under deterioration processes by fouling organisms. The extent of bleaching and its severity was overlaid on priori distribution map. This information allowed us to identify bleached areas, which was then compared with satellite images.

2.3. Satellite data

Two QuickBird satellite images were acquired for multi-temporal analysis; pre-bleaching (September 11, 2005); and post-bleaching (March 28, 2008). The spatial resolution of the multi-spectral images of QuickBird satellite equals to 2.44 m with central values of 485 nm, 560 nm, and 660 nm in red, blue, and green bands, respectively. The water level was 1.21 m and 0.51 m above the mean sea level (MSL) at time of acquisition in 2005 and 2008. Only 2005 image showed favorable low cloud cover and water turbidity conditions, though mild waves were apparent. The other image had partial cloud cover over the study area (11%) and high turbidity due to tide. We favored using only blue and green bands for image interpretation due to low penetration of red band through water (Elvidge et al., 2004; Mishra et al., 2005).

2.4. Image processing and data analysis

A summary of the methods used in the current study is represented in Fig. 2. Pre-processing procedures, i.e., geometric, radiometric, and atmospheric corrections were applied on the satellite images. Several ground control points (GCPs) were selected from an existing vector map (scale = 1:2000) to perform geometric corrections and geo-referencing in the images. For radiometric corrections, ENVI ver. 4.8 software was used to convert the digital number (DN) values to at-sensor radiance L (μW cm^{-2} nm^{-1} sr^{-1}) (Krause, 2005). For atmospheric corrections, the Fast Line-of-Site Atmospheric Analysis of Spectral Hypercubes (FLAASH) module in the same software was utilized to convert the primary radiance to scaled reflectance (Adler-Golden et al., 1999). In addition, features such as terrestrial areas, boats, and jetties, were masked to avoid unpleasant effects on classification (Fig. 3c, d).

The most critical parameter influencing benthic habitat mapping is water column, which attenuates the substrate reflectance values; and this attenuation changes with depth and wavelength of the light passing through water (Lyzenga, 1978, 1981). To minimize this effect, Eq. (1) was applied following Bierwirth et al. (1993) and Purkis and Pasterkamp (2004),

$$R_b = \left(\frac{1}{0.54}R_{rs}(z = a) - \left(1 - e^{-2kz}\right)R_w\right) \Big/ e^{-2kz} \quad (1)$$

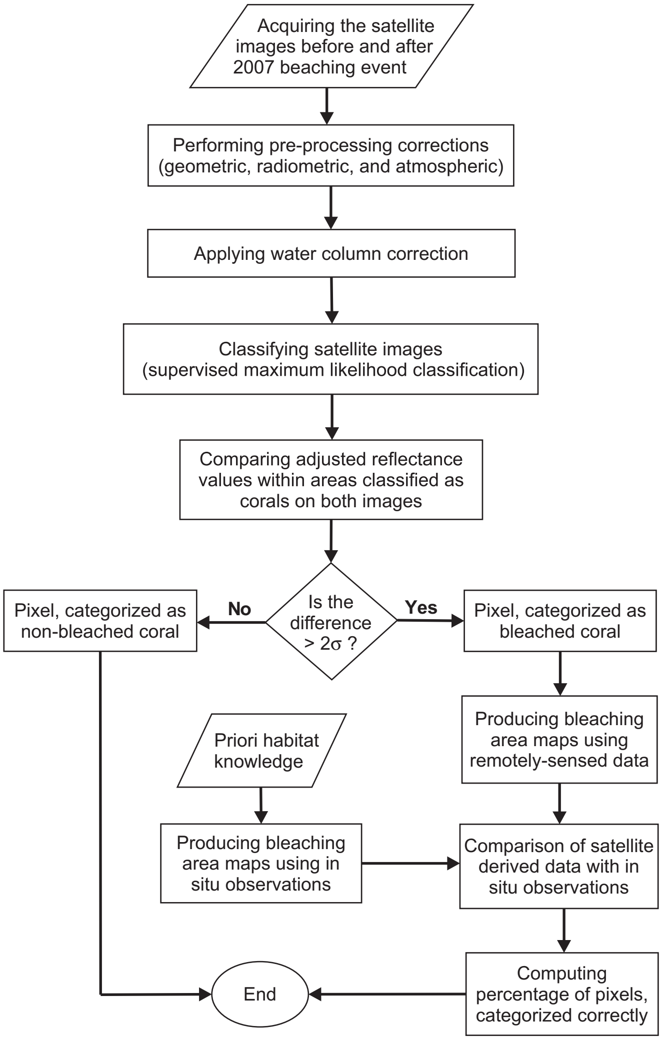

Fig. 2. Concise methodology schema adopted in the current study.

where R_w is water column reflectance of optically deep water; R_b is wet substrate reflectance; $R_{rs}(z = a)$ is remotely sensed effective reflectance just above the water/air boundary; and k, is effective diffuse attenuation coefficient of water body. The k values were calculated using the depth of penetration zone approach proposed by Jupp (1988) and used by Mumby and Edwards (2000) (Table 1). The depth values were extracted from a bathymetric map (scale = 1:2000; provided by Kish Free Zone Organization, No. KLS100D0037). The average reflectance values of an area deeper than 15 m on images were considered as R_w. The optical properties of the study area were assumed to be homogenous (Holden and LeDrew, 2008).

The maximum likelihood classifier was applied to classify main habitat types of the study area (Fig. 3e, f), using over 200 training points. The purpose of classification in our study is to reduce the interferences between sands in detecting bleached corals. Overall accuracy was calculated using testing points which were different than our training data (Table 2). Results were optimized by post-processing operations, such as image filtering (majority filter), which eliminated the salt and pepper effect on classified maps (Eastman et al., 1995).

The differences in reflectance values between two images within the coral classes (ΔR_c) were used to detect bleached corals. The average bottom reflectance values of a homogenous shallow

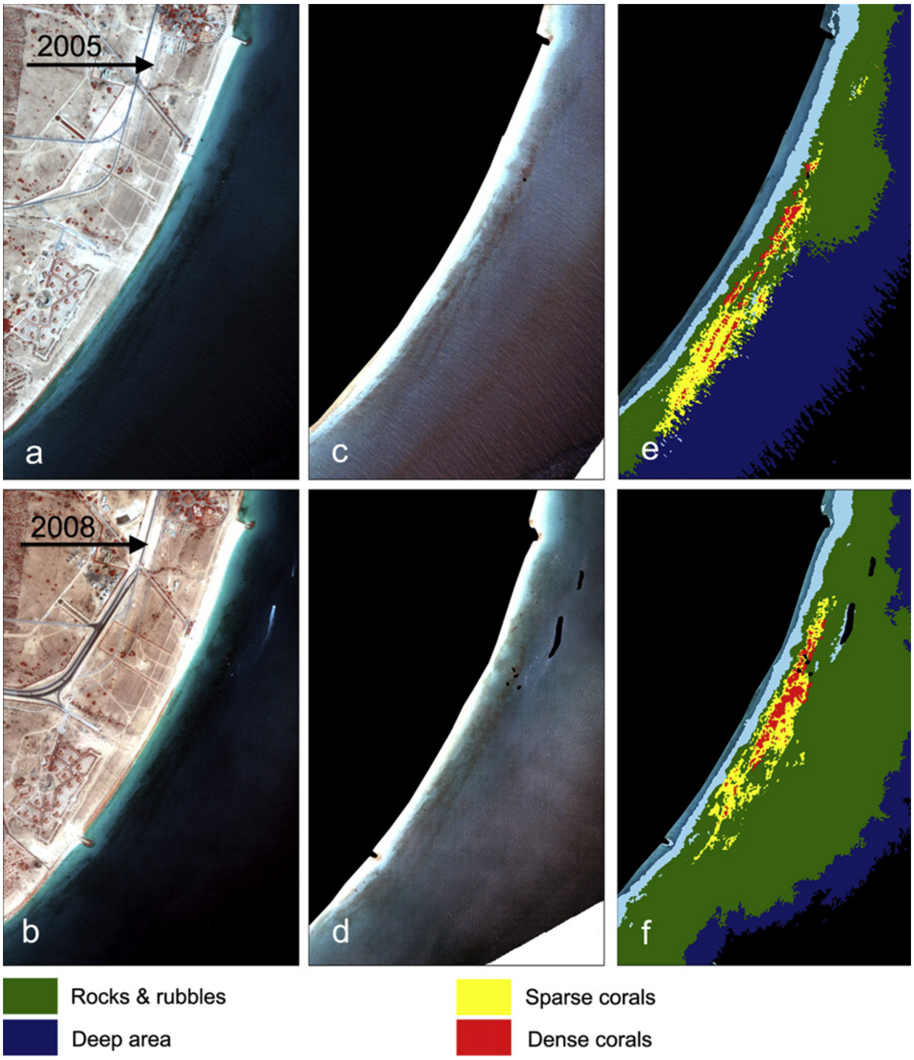

Fig. 3. Image processing from raw to classified image for 2005 and 2008; (a–b) false color composite images (FCC,421) of 2005 and 2008 (FCC,421), (c–d) bottom reflectance values of the 2005 and 2008 images (after radiometric corrections, eliminating land and non-desired objects, and water column corrections), (e–f) classified substrates extracted from in 2005 and 2008.

sandy area (R_s) and mean value of corrected remotely sensed reflectance values of a deep area (R_w) in both images were computed (Table 1), where $\Delta R_s > \Delta R_c > \Delta R_w$ due to the differences in light absorption through water column. The adjusted reflectance values for coral areas ($R_c^{i(\mathrm{adj})}$), were calculated using Eq. (2), to minimize the systematic errors (e.g., differences in sunlight angle, surf, waves), where *i* and *j* refer to the year of image acquisition (*j* is the image with greater values).

$$R_c^{i(\mathrm{adj})} = 0.5 \times \left(\Delta R_s^{j,i} + \Delta R_w^{j,i}\right) + R_c^i \qquad (2)$$

The $R_c^{(\mathrm{adj})}$ in both images were plotted against each other to distinguish bleaching areas (Fig. 4, a and b). The $R_c^{(\mathrm{adj})}$ values in both images were multiplied to enhance the differences in reflectance values simultaneously (Fig. 4, c). The live corals will have lower reflectance values compared with bleached corals in each of the blue and green bands (Holden and LeDrew, 1998; Yamano and Tamura, 2004). Consequently, the pixels representing potential bleaching areas were recognized at a 95% confidence interval. Because of seven months time lapse between the bleaching event (August 2007) and the second satellite image acquisition date (March 2008), all of the white bleached corals were covered by algae. Therefore, in reality these algae-covered corals were detected and were interpreted as bleaching areas later on.

Table 1
The estimated diffuse attenuation values (k), reflectance values of optically deep water (R_w), and reflectance values of shallow sandy areas (R_s) for three visible bands in 2005 and 2008 satellite images.

Year	k (m^{-1})			R_w ($\times 10^2$)			R_s ($\times 10^2$)		
	Red	Green	Blue	Red	Green	Blue	Red	Green	Blue
2005	0.481	0.169	0.133	3.99	4.48	4.72	22.8	34.2	28.1
2008	0.462	0.156	0.129	7.8	7.96	8.1	34.9	41.6	35.9

3. Results

3.1. Multi-temporal processing

The study area can be categorized between Jerlov oceanic water type III and coastal water type 1 (Jerlov, 1976), indicating high turbidity and, therefore, high attenuation of light (Table 1). The R_s and R_w showed different values in each image (Table 1). These differences were due to systematic errors caused by the variation of parameters such as sunlight angle, water quality, and amount of sea

Table 2
Accuracy assessment of classifications and confusion matrix in 2005 and 2008. 1 = Sand, 2 = dense coral, 3 = sparse coral, 4 = rock and rubble, 5 = deep area. The bold numbers represent the number of correctly classified pixels.

2005								2008							
Class	1	2	3	4	5	Total	Producer accuracy (%)	Class	1	2	3	4	5	Total	Producer accuracy (%)
1	**44**	0	1	4	2	51	86.3	1	**40**	1	2	5	1	49	81.6
2	3	**36**	6	4	0	49	73.5	2	2	**31**	11	5	1	50	62
3	0	4	**39**	6	1	50	78	3	1	6	**33**	5	0	45	73.3
4	3	5	2	**41**	1	52	78.9	4	2	7	4	**38**	2	53	71.7
5	1	0	0	3	**49**	53	92.5	5	1	2	0	2	**47**	52	90.4
Total	51	45	48	58	53	**253**		Total	46	47	50	55	51	**249**	
User accuracy (%)	86.3	80.0	81.3	70.7	92.5			User accuracy (%)	87.0	66.0	66.0	69.1	92.2		
Overall accuracy 82.2%, $\kappa = 78.2\%$								Overall accuracy 75.8%, $\kappa = 69.9\%$							

waves in each image. The pre-processing and water column corrections enhanced the image quality (Fig. 3c, d). The corals were classified into two groups: 1) sparse corals, dominant by type a, and c; 2) dense corals, dominant by type b (Fig. 3). A total of 253 and 249 points (not considered as training data) were checked on 2005 and 2008 during extensive field observations. The overall accuracies of the classifications in 2005 and 2008 were 82.2% and 75.8%, respectively. The atmospheric condition of the 2008 image (slightly cloudy) reduced the accuracy, particularly in coral classes with an average of 80.7% in 2005, and 66% in 2008 images (Table 2).

The processed QuickBird satellite images showed an increment in reflectance values of some pixels within coral classes in 2008 in comparison to 2005 in blue and green bands (Fig. 4, a and b). This increase was more distinguishable when multiplied values of two bands were considered (Fig. 4, c). Due to the fact that this anomaly occurred within the coral classes (dense and sparse), it should be the result of bleaching in the coral communities and were identified in 2008 (Fig. 5). Eliminating these points (with reflectance values $>2\sigma$) improved the normality of the remained values (Fig. 4, d, e). As mentioned before, the accuracy of classification for coral classes was ~70%; hence, about 30% of the areas with anomalous reflectance values may contain errors. Because there was no actual bleaching event in 2005, therefore the pixels categorized as bleaching areas in 2005 (8 pixels) were considered as error.

3.2. *Remotely sensed data versus in situ observations*

Priori knowledge of the study area indicated ~85% bleaching in the study area occurred on August 2007. The proposed image processing method was able to detect ~12% bleaching in the area (mixture of coral and non-coral pixels) (Fig. 5). Considering 50% average coral cover for the whole study area, it can be concluded that ~28% of the total bleached corals were detected (Fig. 5).

4. Discussion

This paper discusses the application of multi-temporal satellite images to detect coral bleaching as a potential tool to acquire information of past bleaching events. Accordingly, the multi-spectral satellite data for the pre- and post-bleaching events in 2007 were used to assess the capability and accuracy of using this approach compare to in situ observations at one of the Iranian islands of the Persian Gulf.

The application of remote sensing for detecting bleaching and habitat mapping is limited by sensor characteristics (e.g. spatial, spectral, and temporal resolutions), and environmental complexities (e.g. water quality, depth, and selective absorption) (Holden and LeDrew, 1998; Andréfouët et al., 2001; Yamano and Tamura, 2004). It is known that mapping aquatic vegetation, coral reefs, and general bottom characteristics requires high spatial resolution multi-spectral/hyperspectral imagery (Holden and LeDrew, 1999; Mumby and Edwards, 2002; Mishra et al., 2006, 2007). On the other hand, clarity of the water column is an important factor influencing accuracy and quality of the results (Yamano and Tamura, 2004). One of the drawbacks of using remote sensing in the Persian Gulf is turbidity of the water. An analysis of k among different bands in images, the Persian Gulf waters classifies in between oceanic water type III and coastal water type 1 (Jerlov, 1976), indicating high turbidity and, therefore, high attenuation of light (Table 1). Turbidity decreases the water clarity and increases the water column attenuation effects, consequently diminishes the accuracy of results. To solve the turbidity difficulties, an integration of acoustic systems (e.g. side scan sonar and single/multi-beam echo-sounders), satellite remote sensing, and in situ observations will provide more accurate results (Brown et al., 2011). This approach has been investigated in the Persian Gulf and has proved to be correct (Riegl et al., 2001; Riegl and Purkis, 2005; Purkis and Riegl, 2005). Although, such combined method leads to higher accuracy, it is still limited by extensive field operations and available resources (equipments, technicians, budget, etc.), therefore it might not be cost-effective, especially in remote places along the Iranian coastline.

A further complication is that analyses of a single image might not correctly identify pixels containing both healthy and bleached corals. Identification of bleached corals from carbonate rock and sand is difficult because of their similarity in reflectance (Clark et al., 2000; Rowlands et al., 2008), while, live and dead corals (covered by algae) can be easily separated from sands. Most of the misclassifications occurred between corals (classes 2 & 3) and rubble/rock (class 4), and minimum interference observed between corals and sand (Table 2). This is in agreement with the previous studies which indicated that due to similarities in optical properties of corals and rocks, most interferences during classification occur between these two classes and not between corals and sandy areas (Riegl and Purkis, 2005; Mishra et al., 2006). In the proposed method, the sand class was not considered in bleaching detection, therefore, the interference between bleached corals and sand is at minimum level (Table 2).

Yamano and Tamura (2004) showed that it is difficult to detect bleached corals if the amount of bleaching within an image pixel of the satellite is less than 23%. Andréfouët et al. (2002) showed that underestimation in bleaching detection increases when the resolution decreases. For example, at 2 m resolution aerial photographs, they observed 0.2–12.5% underestimation compare to in situ data. Therefore, to obtain the most accurate results, the resolution should be close to colony average size; and without large bleached colonies

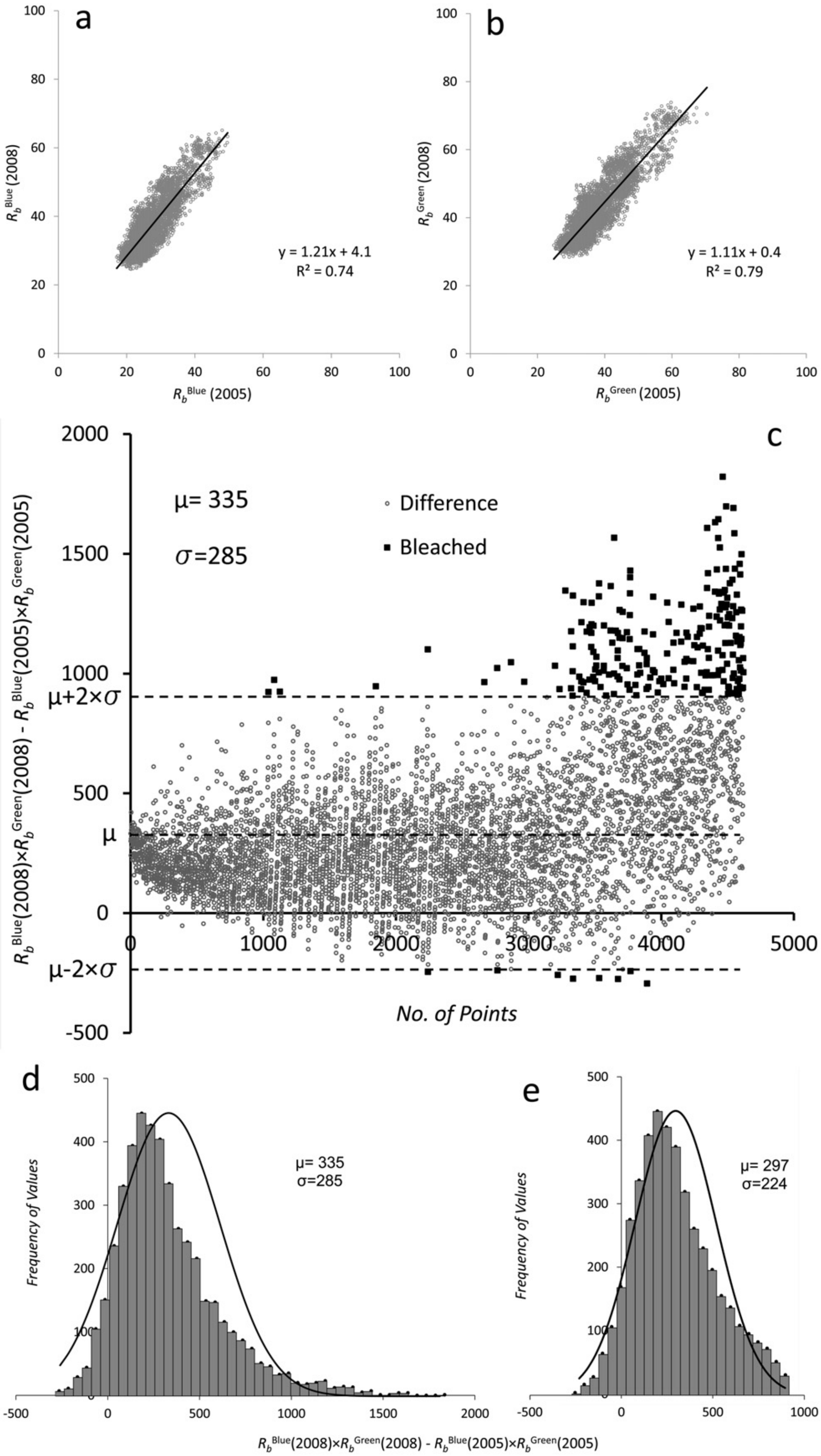

Fig. 4. Relationship between reflectance values. (a) Scatter chart of the corrected bottom reflectance values (R_b) of green band, (b) scatter chart of the corrected bottom reflectance values of blue band, (c) Scatter chart of the multiplied corrected bottom reflectance values in green and blue bands. Pixels more than $2 \times \sigma$ from the average value are indicated by black squares, (d) The multiplied values and normalized values before eliminating bleached corals, (e) Multiplied values and normalized values after eliminating bleached corals.

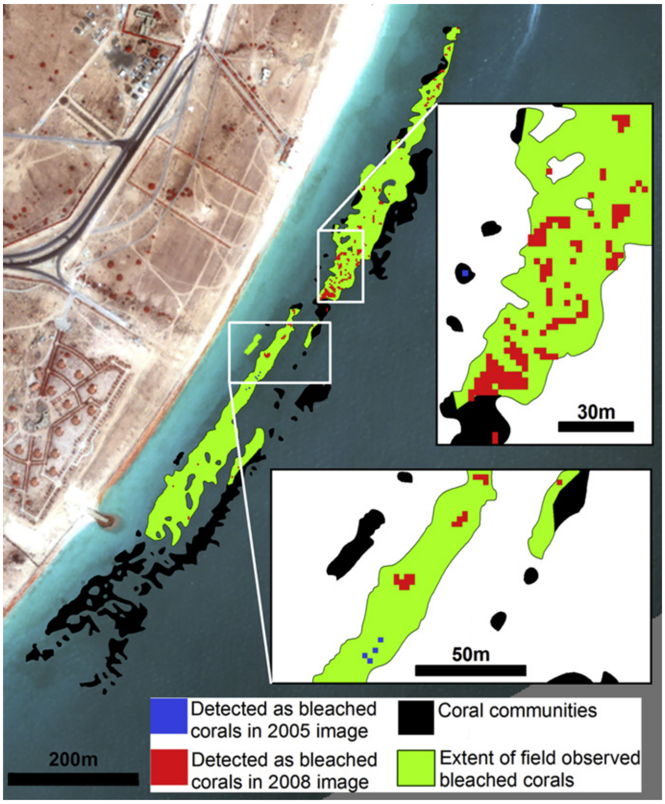

Fig. 5. Comparison of multi-temporal analysis and in situ bleaching extent from field observations.

or contiguous colony structures bleaching event cannot be detected at a resolution coarser than 2 m (Andréfouët et al., 2002). On the other hand, susceptibilities to bleaching are also different among coral taxa (Marshall and Baird, 2000), therefore the bleaching estimation varies according to size, growth form, and susceptibility of the dominant species (Andréfouët et al., 2002). This suggests that the amount of bleaching recognized in satellite image varies across different coral assemblages and therefore comparison of in situ data to satellite data might not be useful unless the boundaries and coverage of each coral assemblage are known. As most of the study area comprises sparse corals and most of these corals have less than 0.5 m diameter size, unless they show high coverage they cannot be detected with high accuracy. Hence, most of the detected bleaching pixels are located in dense coral class where dominated by high cover and large size *Acropora* colonies (Figs. 3e–f, 5). Rowlands et al. (2008) also found that on high-density coral cover the image showed noticeably higher at-sensor radiance than reference image, however, when bleaching was 20% of total cover the radiance did not show any changes.

The PIF approach used by Elvidge et al. (2004) requires the availability of an image acquired during a bleaching event. Our approach is not limited by availability of such image, though having such image will increase the precession and accuracy of final results. Rowlands et al. (2008) followed the same approach, but did not provide any comparison between their tested approach and in situ observations.

Comparison of multi-temporal images allows more accurate assessment of the detection limits for bleached corals in a pixel, because an increase in reflectance will be recorded where bleaching has taken place (Yamano and Tamura, 2004). The patterns of increased radiance associated with bleached coral in bands 1 and 2 in this study support finding elsewhere (Holden and LeDrew, 1998; Elvidge et al., 2004; Rowlands et al., 2008) and when both of the images were considered at the same time this increase is more distinguishable (Fig. 4c). By suing the known spatial distribution of coral habitat avoided the sand/coral interface, and prevented misclassifying bleached coral as sand (Rowlands et al., 2008).

Healthy corals show low reflectance, while bleached corals show higher reflectance (Holden and LeDrew, 1998). If corals do not recover from bleaching, their white carbonate skeleton will be covered by algae in few weeks or months (Clark et al., 2000). The same phenomena happened in our study area. Because of time difference between bleaching event (August 2007) and the post-bleaching image (March 2008), the bleached coral spectral signals were masked by algae. Therefore, we dealt with bleached corals covered with algae and not any white bleached colony in our study (algae-challenged scenario). The similarity of algae color range to live corals leads to complication in distinction between live and dead corals (Clark et al., 2000), however, the proposed approach will eliminate such problems (Fig. 4 c, d). The accuracy of bleaching detection potentially can be increased by decreasing the time laps between post-bleaching image and bleaching event. Although, there were no white bleached corals on 2008 image and all of bleached corals were covered by algae, the proposed method was able to detect 28% bleaching within coral boundaries (Fig. 5). This, suggest that although algae have lower reflectance than bleached corals, it is still higher than the reflectance of live corals at the study area (Fig. 4). Whether this much accuracy is enough to say bleaching happened without any field observations is still subject to more tests and is a matter of user choice.

4.1. Implications for management

As a result of counter clock wise water circulation pattern in the Persian Gulf, and better environmental conditions along the Iranian coastline, coral species richness is higher compare to the southern part (Samimi-Namin and van Ofwegen, 2009, 2012; Riegl et al., 2012). Main Iran coral communities have developed around the remote islands, where field monitoring and in situ observations are not always practical and in some cases even impossible. Our study provides a demonstration of how remote sensing can play a role in monitoring inaccessible and rarely visited coral areas along the Iranian coastline. The 2007 bleaching at northern side of the Persian Gulf caused severe coral mortalities at some of the Iranian islands, while virtually there was no bleaching report from the southern part at the same time (Baker et al., 2008). This suggests that the bleaching patterns and temperature anomalies are not constant throughout the Persian Gulf. Without field observation, the bleaching event demonstrated here could have been easily overlooked and perhaps it is the case for most of Iranian corals and explains the insufficient bleaching records along Iranian coastline. The proposed method can detect major changes in coral communities such as bleaching; even without field observations. Such information can be used by managers for planning further field operations and future data collection. Integrating multi-temporal approach together and SST data set will provide a powerful tool to track bleaching events in the past. Iranian corals are among the least known corals within the Persian Gulf and likely to be the main source of larvae for coral recruitment in the south part and therefore knowledge of bleaching frequency, severity, and distribution is vital and might reveal the whole coral population dynamics and connectivity patterns within the Persian Gulf environment (Sheppard et al., 2010).

5. Conclusion

In this study, multi-temporal remotely sensed images and in situ data sets were combined to produce a spatial pattern of bleaching extent in coral communities at SE of Kish Island, Iran. This is the first time such an approach was tested along the Iranian coastline and the surrounding region. The priori distribution map and coral communities knowledge, made it possible to explore and compare the results with field observations. The study allowed us to explore and assess the usage of multi-temporal satellite images in monitoring bleaching events. The technique proved to be useful for recognizing bleaching, even by using an image acquired several months after the bleaching event, when all white bleached corals were covered by algae. Furthermore, distinguishing coral communities during classification, the interferences between sand and bleached corals; as well as healthy and dead corals was in minimum level. Therefore, by using more images and reducing the time lapses between image acquisition dates and bleaching events, more accurate results can be produced. Combining commercial satellite remote sensing observations with in situ data can produce accurate results and provide baseline information for future studies.

Author contributions

Conceived and designed the experiments: KK KSN. Performed the experiments: KSN KK. Analyzed the data: KK KSN. Contributed reagents/materials/analysis tools: KK KSN BP MM. Wrote the paper: KSN KK BP.

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