Assessing vertical and horizontal movements of algal blooms in a coastal water using satellite remote sensing for optimal operation of desalination plants

H. Chen and M.-H. Park

ABSTRACT

Harmful algal blooms (HABs) are global concerns in coastal waters due to diffuse pollution and climate change. Emerging issues of HABs include their impact on desalination operations for water supply. This study utilizes composite satellite images to detect movement and propagation of algal blooms. Time series images from the Moderate-Resolution Imaging Spectroradiometer (MODIS) were used for monitoring chlorophyll-*a* in the Persian (Arabian) Gulf, which neighboring countries depend upon for desalination as their freshwater resource. Bi-daily MODIS data from the Terra and Aqua satellites were used to detect both vertical migration and horizontal movement of algal blooms. The results will be useful for creating an early warning system for desalination plants to anticipate operating strategies and intake locations to minimize impacts.

Key words | chlorophyll-*a*, desalination, harmful algal blooms, red tide, satellite remote sensing

H. Chen
Department of Civil and Environmental Engineering,
University of Massachusetts Amherst,
Amherst, USA

M.-H. Park (corresponding author)
Department of Civil and Environmental Engineering,
University of California,
Los Angeles,
USA
E-mail: *parkmh@ucla.edu*

INTRODUCTION

Harmful algal blooms (HABs), also known as red tides in coastal waters, are global concerns and have been rapidly growing over the past decades. The expansion of HABs has been reported in many coastal waters worldwide (Okaichi 1989; Smayda 1990; Hallegraeff 2003; Glibert *et al.* 2005; Anderson *et al.* 2008; Richlen *et al.* 2010). Many studies have shown more diverse species and more frequent recurrences of HABs. The increased occurrence of HABs has been due mainly to climate change and anthropogenic impacts. The increase in nutrients from agricultural fertilizer, river discharge, and aquaculture feed can cause algal blooms (Al-Yamani *et al.* 2006). Some algal species outperform other species in higher temperature and/or salinity conditions that can cope with climate change (Seckbach & Oren 2007).

Emerging issues of HABs include their impacts on desalination operations, which are growing due to the increased dependence on desalination plants for water supply (Richlen *et al.* 2010; Villacorte *et al.* 2015b). Seawater reverse osmosis (SWRO) desalination plants are vulnerable to algal toxins and biomass (Villacorte *et al.* 2015b). The presence of algal toxins can cause a treatability problem while organic matter released from algal biomass can pose operational challenges such as biofouling in SWRO membranes (Villacorte *et al.* 2015a, 2015b). These issues can even cause temporary shutdown of SWRO desalination plants (Pankratz 2008). The significance of HAB issues for SWRO plants depends on the incidence, spatial distribution, magnitude and duration of the bloom (Caron *et al.* 2010). Therefore, understanding of HAB occurrences will help SWRO plants avoid damage from HABs and process failures. Monitoring programs should be established along with modeling efforts for predicting bloom trajectory as a forewarning system to allow desalination plants to react accordingly (Villacorte *et al.* 2015b).

Remote sensing has emerged as a new tool for monitoring algal bloom events (Anderson 2009). Satellite remote

doi: 10.2166/ws.2019.092

sensing has been used to monitor the extent and severity of HAB events since it can provide synoptic coverage on a periodic basis. The analysis of remote sensing often requires *in situ* measurements for calibrating from known interferences such as species diversity, various atmospheric conditions, the fluvial nature of the observed content, and the color of dissolved organic matter, which will ensure long-term accuracy of the processed image results.

Satellite remote sensing has been employed to detect HABs using chlorophyll-*a* concentration as a proxy of algal blooms because of its general positive correlation with most algal species (Batten *et al.* 2003). Satellite remote sensing analysis has been conducted for species identification to find dominant species of HABs in coastal waters. For example, satellite remote sensing was applied to identify *Karenia brevis* in Florida (Hu *et al.* 2008), *Cochlodinium polykrikoides* in Korea, Japan and on the northern coast of China (Ahn *et al.* 2006; Siswanto *et al.* 2013) as well as in India and the Persian (Arabian) Gulf (Moradi & Kabiri 2012; Simon & Shanmugam 2012; Zhao *et al.* 2015), and cyanobacteria in US coastal waters (Kutser *et al.* 2006) and the Baltic Sea (Hansson & Hakansson 2007). Certain algae exhibit vertical migration, where they drop and remain at a subsurface level at different times for nutrient and sunlight requirements (Villacorte *et al.* 2015b), which requires frequent remote sensing.

This study aims to utilize satellite images with a correlation between chlorophyll-*a* and algal mass to detect the horizontal distribution and vertical migration of algal blooms. This will establish the platform for a forewarning system in bloom concentration, movement characteristics (surface or vertical migration), and estimated arrival time for desalination plants in the region. The results can be used to inform desalination plants in their decision-making to prevent damage from HABs.

METHODS

Study area

The study area is the Persian Gulf (also known as the Arabian Gulf, the Gulf) (Figure 1). The Gulf has a mean depth of 35 m and maximum depth of 60–80 m (Reynolds 1993; Sheppard *et al.* 2010). Its surface area is 240,000 km^2 with a length of roughly 1,000 km and width of 185–340 km (Smith *et al.* 2007). The Gulf can be divided into northern and southern sections as shown by the front line (Figure 1). River discharges play a major role in local circulation in the northern end, which is shallow (Reynolds 1993). The southern end is impacted by inflow from the Strait of Hormuz, which circulates through the system with a mean retention time of 2.4 years before exiting back to the Gulf of Oman (Sheppard 1993). The Gulf has a high evaporation rate (1.5 m/yr), salinity (>39 psu) and temperature (mean >30 °C) (Brewer & Dyrssen 1985; Smith *et al.* 2007).

The surrounding countries highly depend on the Gulf's water for desalination as their freshwater resource (Lattemann & Höpner 2008; Al Azhar *et al.* 2016). Desalination plants in the Gulf region account for over 45% of the world's desalination capacity (Villacorte *et al.* 2015b), and include both reverse osmosis (RO) membrane and distillation processes. The Shuwaikh Desalination Plant, located in Kuwait Bay (Figure 1), is expected to be impacted by the blooms due to chronic high blooms.

The first HAB event in the Gulf was documented in 1908 and has been a common occurrence in the region since then (D'Silva *et al.* 2012). The Gulf has been experiencing more frequent algal blooms, perhaps as a result of population growth (Al Shehhi *et al.* 2014). The 2008–2009 red tide is the most studied HAB event in recent years (Richlen *et al.* 2010; Zhao *et al.* 2015).

Noctiluca scintillans and *Trichodesmium erythraeum* were two dominating species before 2008 (Al Shehhi *et al.* 2014) whereas *Cochlodinium polykrikoides* became the dominating dinoflagellate species during the red tide event in 2008 (Zhao *et al.* 2015). *C. polykrikoides* have been reported to grow under a wide range of temperatures (Kim *et al.* 2004) and have adapted to survive under high salinity (Richlen *et al.* 2010), aligning with the changing environment of the Gulf region. These recent HAB events have caused the shutdown of multiple desalination plants in the Gulf (Al Shehhi *et al.* 2014).

Satellite data acquisition

Moderate-Resolution Imaging Spectroradiometer (MODIS) is a multi-spectral instrument launched aboard the Terra (launched in 1999) and Aqua satellites (launched in 2002)

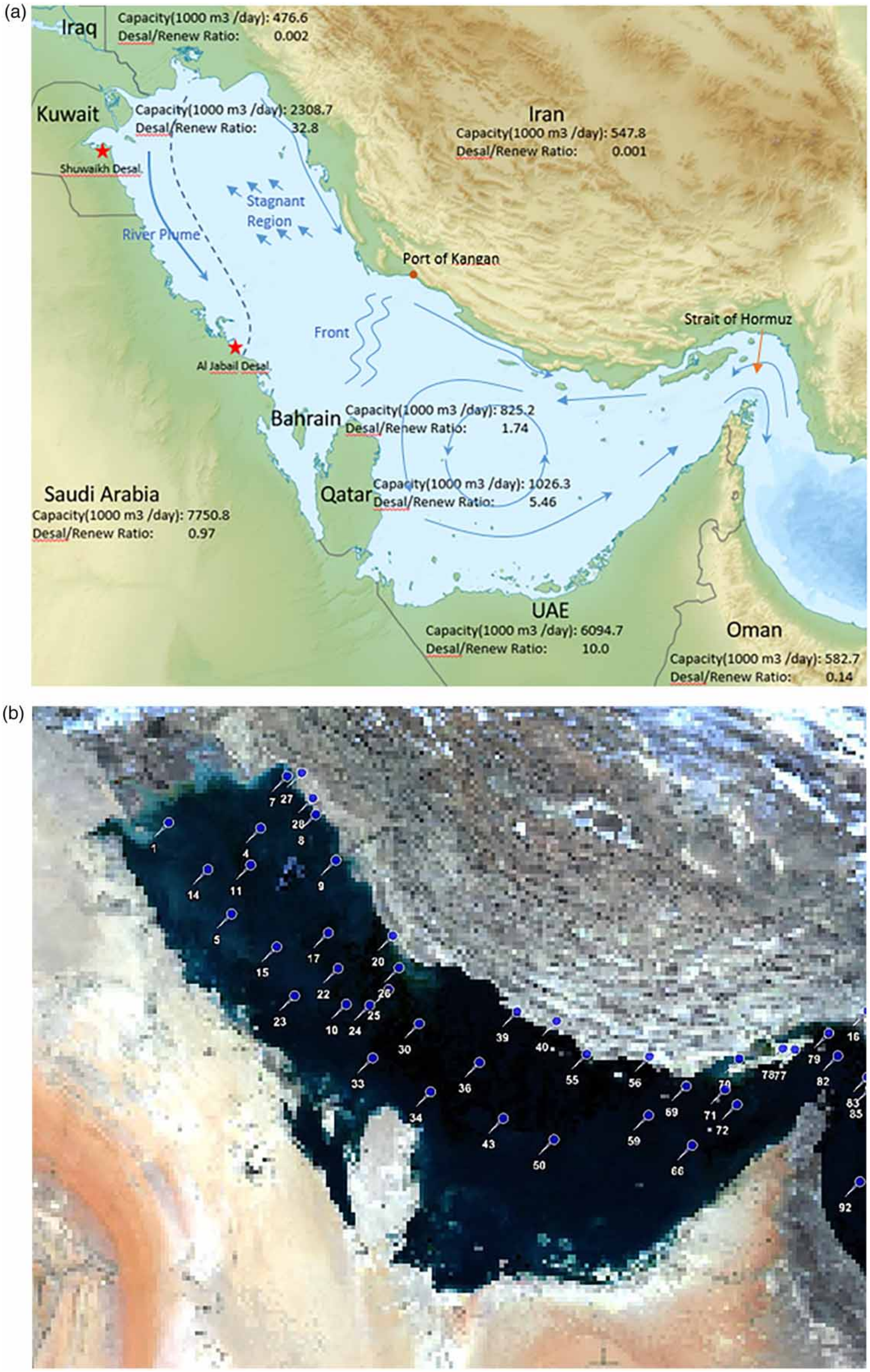

Figure 1 | Study area of the Gulf: (a) the location of selected SWRO plants and flow circulation (modified from Reynolds 1993); (b) the location of field sampling (modified from ROPME 2012).

as part of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) program. Terra/ Aqua MODIS are sun-synchronized, polar orbiting satellites with 36 bands ranging over wavelengths of 400–14,385 nm (Kutser *et al.* 2006). MODIS provides spatial resolution of 250, 500 and 1,000 m, which is common for ocean color analysis and suitable for the study area. MODIS has a daily revisit cycle for the same region. Using MODIS from both Terra and Aqua could provide a bi-daily revisit cycle.

In this study, MODIS data from both Terra (10:30 am local time) and Aqua (1:30 pm local time) satellites were acquired for the Gulf region between latitudes 23.4° and 31°N, and longitudes between 47.2°and 58°E in the bloom years of 2006 and 2008. The MODIS data (Level 1 product) was obtained from the Level 1 and Atmosphere Archive and Distribution System (LAADS) web (https://ladsweb.nascom.nasa.gov/). Cloud coverage of each image was inspected and relatively cloud-free images were selected.

Field sampling data acquisition

Field sampling data for chlorophyll-*a* concentration in winter 2006 were acquired from a previous study (ROPME 2012). They sampled at different depths (Figure 1) and the data sampled at the surface was used for this study. Laboratory processed chlorophyll-*a* samples were measured in accordance with US EPA standard method 445.0 (ROPME 2012). *In situ* chlorophyll-*a* concentration was measured through a TD-700 fluorometer (ROPME 2012). The coincident pairs between the ROPME field data from 2006 (i.e. fluorometer *in situ* measurements) and MODIS data were used to evaluate the remote sensing of bloom events. As the remote sensing of water features near the shore can be influenced by land features and shallow depth, *in situ* measurements collected within 5 km of the coast-line were not used in this study. A total of five stations were selected over the two-day period of February 28th (stations 36 and 39) and March 1st (stations 27, 30, and 33) to find correlation between the remote sensing and the *in situ* chlorophyll-*a* concentrations.

Image processing

The OC3M-547 algorithm was used to estimate the chlorophyll-*a* concentration distribution in the Gulf. OC3M-547 is a standard chlorophyll-*a* algorithm for ocean color (O'Reilly *et al.* 2000) and is currently operated and maintained by the Ocean Color Biology Processing Group (OBPG) (http://oceancolor.gsfc.nasa.gov/cms/). The OC3 algorithm is as follows:

$$Chl\ a = 10^{0.2424-2.7423\times X+1.8017\times X^2+0.0015\times X^3-1.2280\times X^4}$$

$$x = log_{10}\left(\frac{Rrs1}{Rrs2}\right) \quad (1)$$

where $Rrs1$ and $Rrs2$ are the reflectance of the available blue and green wavelengths, respectively. The coefficients are MODIS sensor-specific and are derived from the NASA bio-Optical Marine Algorithm Dataset (NOMAD, http://seabass.gsfc.nasa.gov/wiki/article.cgi?article=NOMAD).

The resulting chlorophyll-*a* concentration distributions were evaluated against the OBPG Level 3 daily chlorophyll-*a* concentration distribution and coincident *in situ* measurements. The chlorophyll-*a* concentration was converted to present the extent and change of blooms above certain thresholds (2.5 μg/L). The resulting consecutive threshold images were then compared to detect their appearance and disappearance between those times. The appearance or disappearance of the chlorophyll-*a* patches with similar extent at the same location over different times was used to detect vertical migration of the bloom. Similarly, the movement of chlorophyll-*a* patches with similar extent from one location to another was measured to determine horizontal migration of the bloom for their velocity and trajectory. The velocity of the bloom movement was calculated by dividing the distance between the two patch centroid cells by the elapsed time between consecutive image results. The trajectory of the bloom movement was estimated using the existing hydrodynamic model in the region (Reynolds 1993). These were used to develop a warning system for desalination plants.

RESULTS AND DISCUSSION

Algal bloom distribution in the Gulf

The chlorophyll-*a* concentration between *in situ* fluorometer measurements and estimates from MODIS readings

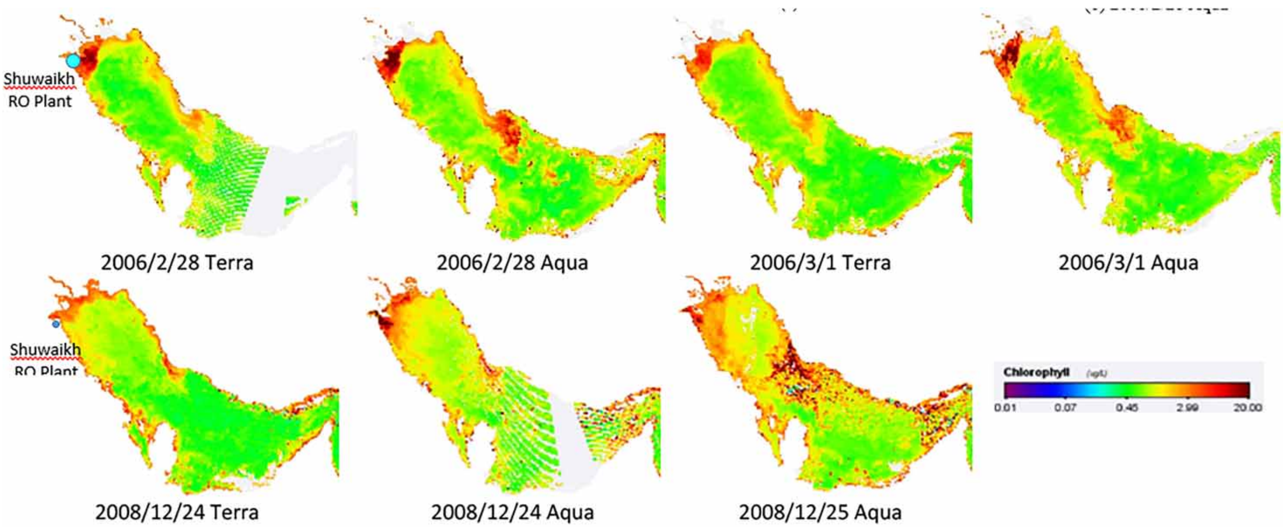

Figure 2 | The distribution of chlorophyll-*a* estimated from MODIS in the Gulf in winter 2006 and 2008.

showed high correlation ($r = 0.9788$, RMSE $= 1.51$). In addition, chlorophyll-*a* concentration between *in situ* fluorometer measurements and laboratory analysis from ROPME sampling in 2006 also showed a high coefficient of determination ($R^2 = 0.9975$, ROPME 2012). These provide confidence in applying the satellite image to estimates of actual chlorophyll-*a* propagation in the Gulf region.

Figure 2 shows the distribution of chlorophyll-*a* concentration in the Gulf in winter in 2006 and 2008. Both years showed high chlorophyll-*a* concentrations in Kuwait Bay (where the intake of the Shuwaikh SWRO plant is located) and the coast around the Port of Kangan in Iran. Kuwait Bay is reported to be a constant hotspot of high chlorophyll-*a* concentration (Zhao *et al.* 2015), which is due mainly to the shallow depth in the northern Gulf in combination with nutrient input from the river plumes (Reynolds 1993). There is no SWRO plant in the Port of Kangan but the algal bloom could affect the SWRO plants located south of Kangan. The distribution of chlorophyll-*a* in winter 2008 shows more spread of bloom over the Gulf compared with 2006 events.

Estimation of bloom migration and its impact on desalination plants

Figure 3 shows bloom change in the time elapsed between consecutive image results: blue and red pixels represent the decline and rise of chlorophyll-*a* patches, respectively, while green and white pixels represent the constant presence and absence of chlorophyll-*a* patches, respectively. The results show constant blooms in Kuwait Bay while there is a daily pattern of repeated cycles of the bloom near the Iranian coast off the Port of Kangan. For the 2006 events, blooms appeared on the surface from late morning (detected by Terra) to early afternoon (detected by Aqua), disappeared from the surface overnight and reappeared the next day at the same location. This demonstrates that frequent satellite remote sensing can detect diurnal migration, which overcomes the limitation of satellite remote sensing that it cannot monitor the subsurface of the water. This location was reported to experience blooms due to the upwelling current providing the nutrient supply to sustain algal growth (Reynolds 1993). In this location, water is stagnant because inflow currents from the Strait of Hormuz meet with the upwelling current (Reynolds 1993). Stagnant water is more prominent for vertical migration than other parts of the Gulf with constant current. The vertical migration phenomenon is of special interest because this affects the location of intakes of potential SWRO plants. Subsurface intake has been suggested as a viable pretreatment for the plants that are vulnerable to HAB occurrence (Villacorte *et al.* 2015b). Finding hotspots for vertical migrations can be used for decision-making in planning or changing the intakes to avoid potential impacts of HABs.

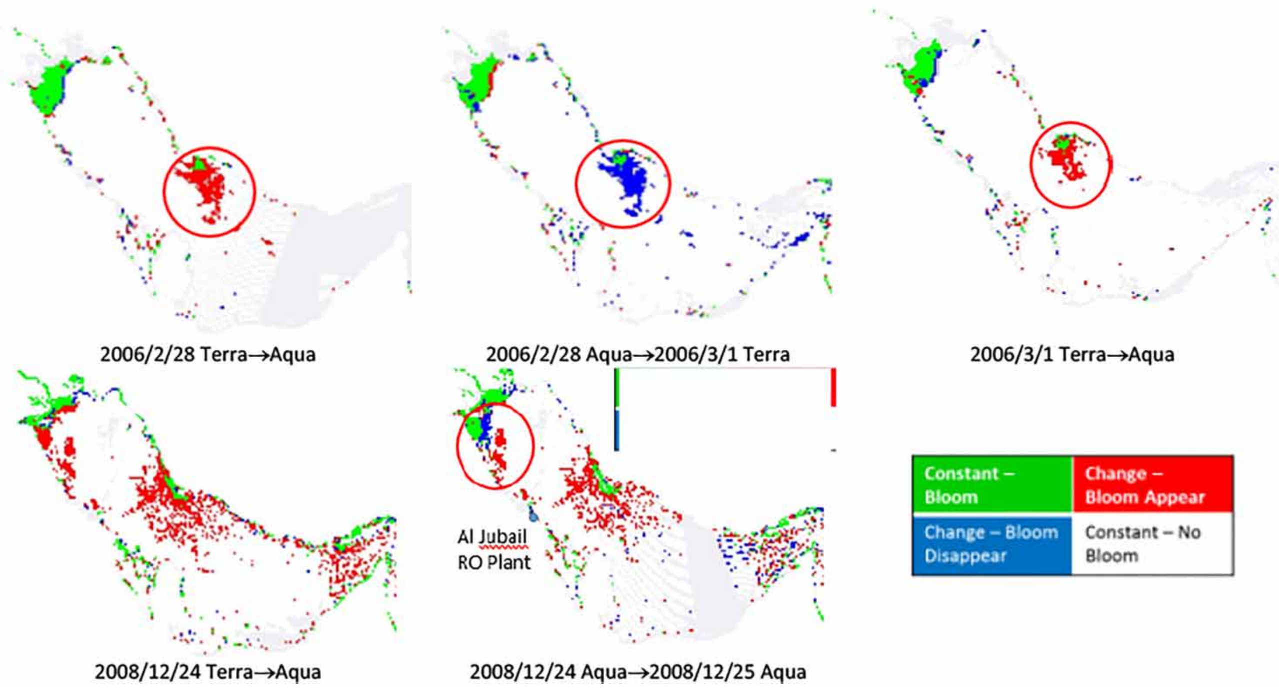

Figure 3 | The movement of chlorophyll-*a* estimated from MODIS in the Gulf in winter 2006 and 2008.

For the 2008 bloom events, the comparison of the MODIS Aqua image results over consecutive days shows the change of bloom patches of similar size and shape, located close to each other. This is evidence of horizontal movement or spread of blooms over a day. The calculated travel velocity of the bloom patch was approximately 0.42 km/h. The direction of the bloom patch movement was south-east from Kuwait Bay, which was in accordance with the diffuse pollutant trajectory along with the river plume as shown in Figure 1 (Reynolds 1993). The horizontal movement increases the likelihood of high bloom inflow to the Al Jubail SWRO plant in Saudi Arabia (Figure 1). The derived trajectory and velocity of bloom movement can be used to develop a warning system for SWRO desalination plants of the possible bloom impact, which will assist the plants in making decisions to avoid bloom impacts.. Coupling a hydrodynamic model of the Gulf with remote sensing of the initiation of bloom aggregation can provide a warning system for desalination plants with anticipated magnitude and arrival time of blooms.

Despite having the ability of near real-time monitoring and vast spatial coverage, two key challenges remain in utilizing remotely sensed data to monitor bloom change: cloud coverage can prevent daily monitoring; and limited *in situ* measurements for calibrating and validating remote sensing analysis are available.

CONCLUSION

HAB events have been a recurring phenomenon in the Gulf region as well as other parts of the world. This study focused on the impact of HAB events on desalination plants. The extent of the HAB event and major hotspots determined from time-series satellite imagery as introduced in this study is useful for predicting movement patterns of the observed blooms: (1) by identifying horizontal movement and/or vertical migration and (2) by calculating anticipating travel velocity and trajectory of the bloom movement. This can be used for developing a warning system to assist RO desalination plants and regional water utilities in determining operation strategies to minimize the bloom impact in a short-term perspective, and location of intakes to avoid unfavorable intake conditions in a long-term perspective. This study shows that satellite remote sensing can be used to construct a region-wide monitoring program for all RO desalination plants and future water utilities in the region.

Simple remote sensing using chlorophyll-*a* concentrations as proxy for HABs is useful because both toxic and non-toxic algal blooms pose serious threats to RO desalination plants, which is the current dominating desalination mechanism. This study will be highly useful in locations where RO desalination is an important source of water supply. Information from this study should be used to inform desalination plants and water utilities in modifying construction plans and locations, as well as modifying current systems in response to predicted patterns, occurrences, distribution, and forecast trajectory and velocity of movement.

This study showed the practice of using a low spatial resolution, high temporal resolution satellite as a monitoring system. The high temporal resolution (bi-daily) enables rapid detection of horizontal movement and vertical migration of HABs to establish a forewarning system in near real time with large spatial coverage. Future directions are suggested to establish geostationary satellites such as the Geostationary Ocean Color Imager (GOCI) launched over the Korean peninsula, which will give frequent and constant coverage of the area of interest, and which will be a valuable asset in establishing an HAB monitoring system in real time. The use of unmanned aerial vehicles with frequent monitoring can also be an alternative. Future application of this study can be improved using more frequent monitoring of water that can improve our understanding of the dynamics of HABs and development of early warning systems.

ACKNOWLEDGEMENT

This project was funded by the Korea Agency for Infrastructure Technology Advancement. The authors would like to thank Maryam Ghashghaie at Bu Ali Sina University for assisting data collection.

REFERENCES

Ahn, Y.-H., Shanmugam, P., Ryu, J.-H. & Jeong, J. C. 2006 Satellite detection of harmful algal bloom occurrences in Korean waters. *Harmful Algae* **5**, 213–231.

Al Azhar, M., Temimi, M., Zhao, J. & Ghedira, H. 2016 Modeling of circulation in the Arabian Gulf and the Sea of Oman: skill assessment and seasonal thermohaline structure. *J. Geophys. Res. Oceans* **121** (3), 1700–1720.

Al Shehhi, M. R., Gherboudj, I. & Ghedira, H. 2014 An overview of historical harmful algal blooms outbreaks in the Arabian Seas. *Mar. Pollut. Bull.* **86** (1–2), 314–324.

Al-Yamani, F., Subba Rao, D. V., Mharzi, A., Ismail, W. & Al-Rifaie, K. 2006 Primary production off Kuwait, an arid zone environment, Arabian Gulf. *Int. J. Oceans Oceanogr.* **1** (1), 67–85.

Anderson, D. M. 2009 Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean Coast. Manage.* **52** (7), 342–347.

Anderson, D. M., Burkholder, J. M., Cochlan, W. P., Glibert, P. M., Gobler, C. J., Heil, C. A., Kudela, R. M., Parsons, M. L., Rensel, J. E. J., Townsend, D. W., Trainer, V. L. & Vargo, G. A. 2008 Harmful algal blooms and eutrophication: examining linkages from selected coastal regions of the United States. *Harmful Algae* **8**, 39–53.

Batten, S. D., Clark, R., Flinkman, J., Hays, G., John, E., John, A. W. G., Jonas, T., Lindley, J. A., Stevens, D. P. & Walne, A. 2003 CPR sampling: the technical background, materials and methods, consistency and comparability. *Prog. Oceanogr.* **58**, 193–215.

Brewer, P. G. & Dyrssen, D. 1985 Chemical oceanography of the Persian Gulf. *Prog. Oceanog.* **14**, 41–55.

Caron, D. A., Garneau, M.-È., Seubert, E., Howard, M. D. A., Darjany, L., Schnetzer, A., Cetinić, I., Filteau, G., Lauri, P., Jones, B. & Trussell, S. 2010 Harmful algae and their potential impacts on desalination operations off southern California. *Water Res.* **44**, 385–416.

D'Silva, M. S., Anil, A. C., Naik, R. K. & D'Costa, P. M. 2012 Algal blooms: a perspective from the coasts of India. *Nat. Hazard.* **63**, 1225–1253.

Glibert, P. M., Anderson, D. M., Gentien, P., Granéli, E. & Sellner, K. G. 2005 The global, complex phenomena of harmful algal blooms. *Oceanogr.* **18** (2), 136–147.

Hallegraeff, G. M. 2003 Harmful algal blooms: a global overview. In: *Manual on Harmful Marine Microalgae* (G. M. Hallegraeff, D. M. Anderson & A. D. Cembella, eds), UNESCO Publishing, Paris, France, pp. 25–49.

Hansson, M. & Hakansson, B. 2007 The Baltic Algae Watch System – a remote sensing application for monitoring cyanobacterial blooms in the Baltic Sea. *J. Appl. Remote Sens.* **1** (1), 011507.

Hu, C., Luerssen, R., Muller-Karger, F. E., Carder, K. L. & Heil, C. A. 2008 On the remote monitoring of *Karenia brevis* blooms of the west Florida shelf. *Cont. Shelf. Res.* **28** (1), 159–176.

Kim, D.-I., Matsuyama, Y., Nagasoe, S., Yamaguchi, M., Yoon, Y.-H., Oshima, Y., Imada, N. & Honjo, T. 2004 Effects of temperature, salinity and irradiance on the growth of the harmful red tide dinoflagellate *Cochlodinium polykrikoides* Margalef (Dinophyceae). *J. Plankton Res.* **26** (1), 61–66.

Kutser, T., Metsamaa, L., Strömbeck, N. & Vahtmäe, E. 2006 Monitoring cyanobacterial blooms by satellite remote sensing. *Estuar. Coast Shelf. Sci.* **67**, 303–312.

Lattemann, S. & Höpner, T. 2008 Environmental impact and impact assessment of seawater desalination. *Desalination* **220** (1–3), 1–15.

Moradi, M. & Kabiri, K. 2012 Red tide detection in the Strait of Hormuz (east of the Persian Gulf) using MODIS fluorescence data. *Int. J. Remote Sens.* **33** (4), 1015–1028.

Okaichi, T. 1989 Red tide problems in the Seto Inland Sea, Japan. In: *Red Tides: Biology, Environmental Science and Toxicology* (T. Okaichi, D. M. Anderson & T. Nemoto, eds), Elsevier, New York, USA, pp. 137–142.

O'Reilly, J. E., Maritorena, S., O'Brien, M. C., Siegel, D. A., Toole, D., Menzies, D., Smith, R. C., Mueller, J. L., Mitchell, B. G., Kahru, M., Chavez, F. P., Strutton, P., Cota, G. F., Hooker, S. B., McClain, C. R., Carder, K. L., Müller-Karger, F., Harding, L., Magnuson, A., Phinney, D., Moore, G. F., Aiken, J., Arrigo, K. R., Letelier, R. & Culver, M. 2000 *SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3*. SeaWiFS Postlaunch Technical Report Series 11, NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Pankratz, T. 2008 Red tides close desal plants. *Water Desalination Report* **44** (44).

Reynolds, R. M. 1993 Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman – results from the *Mt Mitchell* expedition. *Mar. Pollut. Bull.* **27**, 35–59.

Richlen, M. L., Morton, S. L., Jamali, E. A., Rajan, A. & Anderson, D. M. 2010 The catastrophic 2008–2009 red tide in the Arabian gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate *Cochlodinium polykrikoides*. *Harmful Algae* **9**, 163–172.

ROPME 2012 *ROPME Oceanographic Cruise – Winter 2006*. ROPME/GC-14/7, Technical Report No. 4, Regional Organization for the Protection of the Marine Environment, Kuwait.

Seckbach, J. & Oren, A. 2007 Oxygenic photosynthetic microorganisms in extreme environments. In: *Algae and Cyanobacteria in Extreme Environments* (J. Seckbach, ed.), Springer, Dordrecht, The Netherlands, pp. 3–25.

Sheppard, C. R. C. 1993 Physical environment of the Gulf relevant to marine pollution: an overview. *Mar. Pollut. Bull.* **27**, 3–8.

Sheppard, C., Al-Husiani, M., Al-Jamali, F., Al-Yamani, F., Baldwin, R., Bishop, J., Benzoni, F., Dutrieux, E., Dulvy, N. K., Subba Rao, D. V., Jones, D. A., Loughland, R., Medio, D., Nithyanandan, M., Pilling, G. M., Polikarpov, I., Price, A. R. G., Purkis, S., Riegl, B., Saburova, M., Namin, K. S., Taylor, O., Wilson, S. & Zainal, K. 2010 The Gulf: a young sea in decline. *Mar. Pollut. Bull.* **60** (1), 13–38.

Simon, A. & Shanmugam, P. 2012 An algorithm for classification of algal blooms using MODIS-Aqua data in oceanic waters around India. *Adv. Remote Sens.* **1**, 35–51.

Siswanto, E., Ishizaka, J., Tripathy, S. C. & Miyamura, K. 2013 Detection of harmful algal blooms of *Karenia mikimotoi* using MODIS measurements: a case study of Seto-Inland Sea, Japan. *Remote Sens. Environ.* **129**, 185–196.

Smayda, T. J. 1990 Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic. In: *Toxic Marine Phytoplankton* (E. Granéli, B. Sundström, L. Edler & D. M. Anderson, eds), Elsevier, New York, USA, pp. 29–40.

Smith, R., Purnama, A. & Al-Barwani, H. H. 2007 Sensitivity of hypersaline Arabian Gulf to seawater desalination plants. *Appl. Math. Model* **31** (10), 2347–2354.

Villacorte, L. O., Neu, T. R., Kleijn, J. M., Winters, H., Ekowati, Y., Amy, G. L., Schippers, J. C. & Kennedy, M. D. 2015a Characterisation of algal organic matter produced by bloom-forming marine and freshwater algae. *Water Res.* **73**, 216–230.

Villacorte, L. O., Tabatabai, S. A. A., Anderson, D. M., Amy, G. L., Schippers, J. C. & Kennedy, M. D. 2015b Seawater reverse osmosis desalination and (harmful) algal blooms. *Desalination* **360**, 61–80.

Zhao, J., Temimi, M. & Ghedira, H. 2015 Characterization of harmful algal blooms (HABs) in the Arabian Gulf and the Sea of Oman using MERIS fluorescence data. *ISPRS. J. Photogramm. Remote Sens.* **101**, 125–136.

First received 15 August 2018; accepted in revised form 12 June 2019. Available online 26 June 2019