Science of the Total Environment xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A new approach for the estimation of phytoplankton cell counts associated with algal blooms

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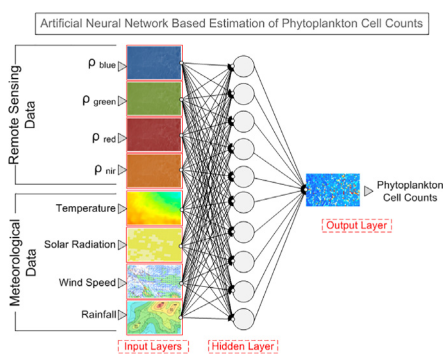
HIGHLIGHTS

- Estimation of phytoplankton cell counts using satellite and meteorological data
- Relationship between phytoplankton cells and water quality parameters
- Hotspots for the large number of red tide incidents were mapped.
- Proposed method can be adopted for routine quantitative estimation of algal blooms.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 November 2016
Received in revised form 27 January 2017
Accepted 22 February 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Coastal water
Red tides
Harmful algal blooms
Phytoplankton cells
Remote sensing

ABSTRACT

This study proposes a method for estimating phytoplankton cell counts associated with an algal bloom, using satellite images coincident with in situ and meteorological parameters. Satellite images from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Operational Land Imager (OLI) and HJ-1 A/B Charge Couple Device (CCD) sensors were integrated with the meteorological observations to provide an estimate of phytoplankton cell counts. All images were atmospherically corrected using the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) atmospheric correction method with a possible error of 1.2%, 2.6%, 1.4% and 2.3% for blue (450–520 nm), green (520–600 nm), red (630–690 nm) and near infrared (NIR 760–900 nm) wavelengths, respectively. Results showed that the developed Artificial Neural Network (ANN) model yields a correlation coefficient (R) of 0.95 with the in situ validation data with Sum of Squared Error (SSE) of 0.34 cell/ml, Mean Relative Error (MRE) of 0.154 cells/ml and a bias of −504.87. The integration of the meteorological parameters with remote sensing observations provided a promising estimation of the algal scum as compared to previous studies. The applicability of the ANN model was tested over Hong Kong as well as over Lake Kasumigaura, Japan and Lake Okeechobee, Florida USA, where algal blooms were also reported. Further, a 40-year (1975–2014) red tide occurrence map was developed and revealed that the eastern and southern waters of Hong Kong are more vulnerable to red tides. Over the 40 years, 66% of red tide incidents were associated with the *Dinoflagellates* group, while the remainder were associated with the *Diatom* group (14%) and several other minor groups (20%). The developed technology can be applied to other similar environments in an efficient and cost-saving manner.

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http://dx.doi.org/10.1016/j.scitotenv.2017.02.182
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1. Introduction

Algal blooms, Harmful algal blooms (HABs) or red tides are one of the most serious environmental problems in coastal and inland waters due to their adverse economic and environmental impacts on water bodies (Pearson et al., 2001). Algal blooms are well adapted for growth in nutrient rich coastal, inland and slow-flowing waters and often form mass populations during summer and autumn in temperate latitudes (Havens, 2008). Increased turbidity due to an algal bloom may cause the deterioration of water quality for drinking, mariculture, and sports activities (Carmichael, 2001). Among various problems, the amount and distribution of algal blooms is of primary concern for water and/or harbour management agencies.

Hong Kong is a thriving international port, but still supports diverse habitats in its coastal waters. Extensive algal blooms or red tides occur from March to May and October to November every year in and around Hong Kong's coastline (Nazeer and Nichol, 2016a). These algal blooms are mostly dominated by *Dinoflagellates* and *Diatoms* groups of phytoplankton (HKEPD, 2016a), which cause massive mortalities of aquaculture fish and pose adverse ecological and health impacts. In 1988, eighty-eight red tide incidents, the highest ever, were observed in Hong Kong. In the most recent red tide incidents from December 2015 to February 2016, >220 tons of fish kills were reported from all mariculture zones of Hong Kong (SCMP, 2016). Local fish farmers claim this incident to be the worst "unnatural disaster" to affect their livelihoods. More than 200 fishermen had to apply for emergency relief, costing the local government HK$ 1.37 million (AFCD, 2016a).

Several studies have demonstrated techniques to detect the red tide incidents using in situ Water Quality Parameters (WQP) including Chlorophyll-a (Chl-a), dissolved oxygen, total inorganic nitrogen, water column transparency and other nutrients (Lui et al., 2007; Wong et al., 2007; Muttil and Lee, 2005; Lee et al., 2003). In Hong Kong, red tide incidents are reported by the public, mariculturists and/or by government departments. The Hong Kong Agriculture, Fisheries and Conservation Department (AFCD) collects phytoplankton cell count data after receiving reports.

Satellite remote sensing is able to provide synoptic measurements of the extent of an algal bloom beyond that of conventional shipboard measurements. The application of remote sensing to algal bloom detection was first demonstrated by Mueller, 1979 who used an experimental airborne instrument developed to simulate the Coastal Zone Color Scanner, and captured an algal bloom over southwest Florida. Satellite based detection was subsequently applied in different studies with other satellite sensors, e.g. Medium Resolution Imaging Spectrometer (MERIS), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Landsat Thematic Mapper (TM) and Coastal Zone Color Scanner (CZCS) (Wynne et al., 2013; Binding et al., 2011; Tang et al., 2004; Vincent et al., 2004; Kopelevich et al., 2002). It has been reported that an algal bloom can be detected using a satellite sensor with phytoplankton cell counts as low as 50 cells/millilitre (cells/ml) (Stumpf and Tomlinson, 2007; Tester et al., 1998).

Algae-laden waters have four distinct scattering and absorption features as compared to clear water i.e. a low reflectance between 400 and 500 nm, reflectance maximum around 550 nm caused by low absorption due to the algae, absorption around 670 nm due to Chl-a, and a prominent reflectance maximum around 700 nm due to high concentration of phytoplankton in the water column and due to the algal scum (Han, 1997). Due to the characteristic reflectivity of phytoplankton dominated waters, several indices have been formulated for monitoring algal blooms, such as the Maximum Chlorophyll Index (MCI) (Gower et al., 2005), Cyanobacteria Index (CI) (Wynne et al., 2008), Floating Algae Index (FAI) (Hu, 2009) and the Maximum Peak Height (MPH) algorithm (Matthews et al., 2012).

Although currently existing indices can be used to map the extent of an algal bloom, they are unable to quantify the actual cell counts of the phytoplankton associated with an algal bloom. In addition, previous studies conducted over Hong Kong (Lui et al., 2007; Wong et al., 2007; Lee et al., 2003; Muttil and Lee, 2005), were found to be limited for red tide monitoring, i.e. (i) these studies are based on the usage of in situ WQP data, and the collection of such in situ WQP data itself, is tiresome, costly and time consuming, (ii) these studies are designed mainly for three regions of Hong Kong i.e. Kat O, Tolo Harbour and Lamma Island, while it has been observed that most of the red tide incidents are not limited to these three regions but have wider coverage over Hong Kong.

Remote sensing thus provides an opportunity for estimation of red tides, of which some studies have been reported over the Chinese marginal seas (Tang et al., 2006; Wang et al., 2007; Wei et al., 2008) and Hong Kong (Tang et al., 2003). However, these studies have been mainly conducted for an episodic event, and used coarse spatial resolution (1.1 km) satellite data for the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Advanced Very High Resolution Radiometer (AVHRR).

This study aims to (i) use medium spatial resolution (30 m) Landsat and HJ-1A/B imagery to develop a numerical model which is able to estimate phytoplankton cell counts for red tide affected areas, (ii) explore the relationship between red tides and different water properties (i.e. physical, chemical and biological), and (iii) develop a map of the causative species of red tide incidents in Hong Kong.

2. Study area

Hong Kong is a special administrative region of Mainland China, located east of the Pearl River estuary. It has a complex marine environment due to terrestrial discharges from the Pearl River in the west, urban pollutants in the centre and the relatively clearer waters of the South China Sea in the east (Pan et al., 2014). There are 26 marine fish culture zones in Hong Kong whose production amounted to HK$ 105 million in 2015 (GovHK, 2016). Thus, a significant economic loss is expected if severe red tide incidents continue.

Over the coastal waters of Hong Kong, a total of 898 red tide incidents were reported from 1975 to 2014. Among these, twenty-seven were associated with fish kills. Of the 80 phytoplankton species known to cause red tide incidents in Hong Kong, fifty-nine are considered harmless and twenty-one are considered harmful or toxic. Among the harmful/toxic species, five species have caused the fish kills and the other two have caused toxic contamination of shellfish (Fig. 1) (AFCD, 2016b).

3. Data used

3.1. Satellite data

This study used archived datasets for Landsat-5 (L5) Thematic Mapper (TM), Landsat-7 (L7) Enhanced Thematic Mapper Plus (ETM+), Landsat-8 (L8) Operational Land Imager (OLI) and HJ-1A/B Charge Couple Device sensors (hereafter referred as HJ-1 CCD) for red tide monitoring. The L5 TM, L7 ETM+ and L8 OLI were launched in March 1984, April 1999 and February 2013, respectively. The three sensors have a spatial resolution of 30 m for multispectral bands but all ETM+ acquisitions acquired after 31 May 2003 suffered from failure of the scan line corrector, causing a loss of ≈22% of the scene (Chander et al., 2009). The HJ-1A/B satellites launched in September 2008 carried four CCD cameras (i.e. CCD1 and CCD2 for HJ-1A and similar for HJ-1B). Apart from Band 1 of the HJ-1 CCDs (B1 = 475 nm), which is ≈10 nm wider than that of Landsat TM/ETM+/OLI (485 nm), the other three bands are identical (B2 = 560 nm, B3 = 660 nm and B4 = 830 nm). The spatial resolution of the four CCD sensors matches the four bands of Landsat TM/ETM+ (B1, B2, B3 and B4) and OLI (B2, B3, B4 and B5). The side rotation feature (±30°) of HJ-1A/B CCDs confers an advantage over Landsat, by shortening the revisit time from 16 days to 48 hr or less (Nazeer and Nichol, 2015).

Please cite this article as: Nazeer, M., et al., A new approach for the estimation of phytoplankton cell counts associated with algal blooms, Sci Total Environ (2017), http://dx.doi.org/10.1016/j.scitotenv.2017.02.182