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Assessing and refining the satellite-derived massive green macro-algal coverage in the Yellow Sea with high resolution images

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ABSTRACT

During over the past 10 years, the massive green macro-algal bloom has regularly occurred in the Yellow Sea, the spatial coverage of which is mainly derived by the remote sensing community from satellite images with moderate/low resolution (30-m–1000-m), such as the 250-m-resolution MODIS (Moderate Resolution Imaging Spectroradiometer). In this paper, the MODIS estimates are compared for the first time with the concurrent high resolution (3-m) airborne Synthetic Aperture Radar (SAR) data. We find that the MODIS results are overestimated by more than a factor of 3 when each algae pixel is assumed to be pure (i.e. 100% algae cover), whereas the overestimation is significantly reduced to 1.14 when the pure pixel assumption is abandoned and the genuine (fractional) algae coverage is derived with the linear pixel un-mixing method. These results, together with the re-sampling processing of the high resolution images, indicate that the mixed pixel effect, that is inherent with images with moderate and low resolutions, is the key factor for the satellite extraction of the macro-algae coverage, and these findings are further confirmed by the satellite data with different resolutions. Besides, significant correlations (R^2 > 0.9) are found between the macro-algae coverage from 3-m resolution SAR images and those from concurrent satellite images with various resolutions (30-m–1000-m) under the pure pixel assumption, which provides an alternative statistics-based method (in addition to the linear pixel un-mixing) for the accurate macro-algae coverage extraction from satellite images with coarse resolution (e.g. HJ-1 CCD, AQUA MODIS, COMS GOCI). This new method is independently validated with high resolution optical images, and applied to derive the annual maxima of the massive green macro-algal bloom areas (fractional coverage) in the Yellow Sea from 2007 to 2016, which ranges from 45.6 to 732.9-km^2 with an average of 247.9 ± 199.3-km^2.

1. Introduction

During the past 10 years, a massive green macro-algal bloom has regularly occurred in the Yellow Sea (Hu et al., 2010; Keesing et al., 2011; Xing and Hu, 2016). Identifying the cause of the algal outbursts, and addressing the environmental impacts and implications, has drawn extensive attention from both the scientific communities and the public (Sun et al., 2008; Hu and He, 2008; Liu et al., 2009; Ye et al., 2008, 2011). In much of the research, satellite data have played an important role because of the synoptic view they provide, and the repeated observations. With the help of remote sensing data, the pattern of the macro-algal bloom, especially its origin and development process (Keesing et al., 2011; Liu et al., 2016; Son et al., 2012, 2015; Qi et al., 2016), is becoming much clearer, and thus the early warning as well as prevention of this ecological phenomenon has been substantially improved (e.g. Wang et al., 2015).

In the remote sensing research and the operational satellite monitoring of the macro-algae bloom, optical images of MODIS (Moderate Resolution Imaging Spectroradiometer) with a 250-m spatial resolution are most popular (e.g. Hu, 2009; Shi and Wang, 2009; Hu et al., 2017;Qi et al., 2016; Wang and Hu, 2016), although other optical images with moderate/low resolution (30-m–500-m) are also adopted, such as Landsat TM (e.g. Hu et al., 2016), HJ-1 CCD (e.g. Xing and Hu, 2016), and COMS GOCI (e.g. Son et al., 2012, 2015).

From satellite optical images, the floating macro-algae pixels can be differentiated from the surrounding water and thus delineated, using the various vegetation indices, such as NDVI (normalized difference vegetation index) (e.g. Cui et al., 2012), FAI (floating algal index) (Hu, 2009), and SAI (Scaled Algae Index) (Garcia et al., 2013). By multiplying the pixel size (e.g. 250 × 250-m^2 for MODIS, and 30 × 30-m^2 for

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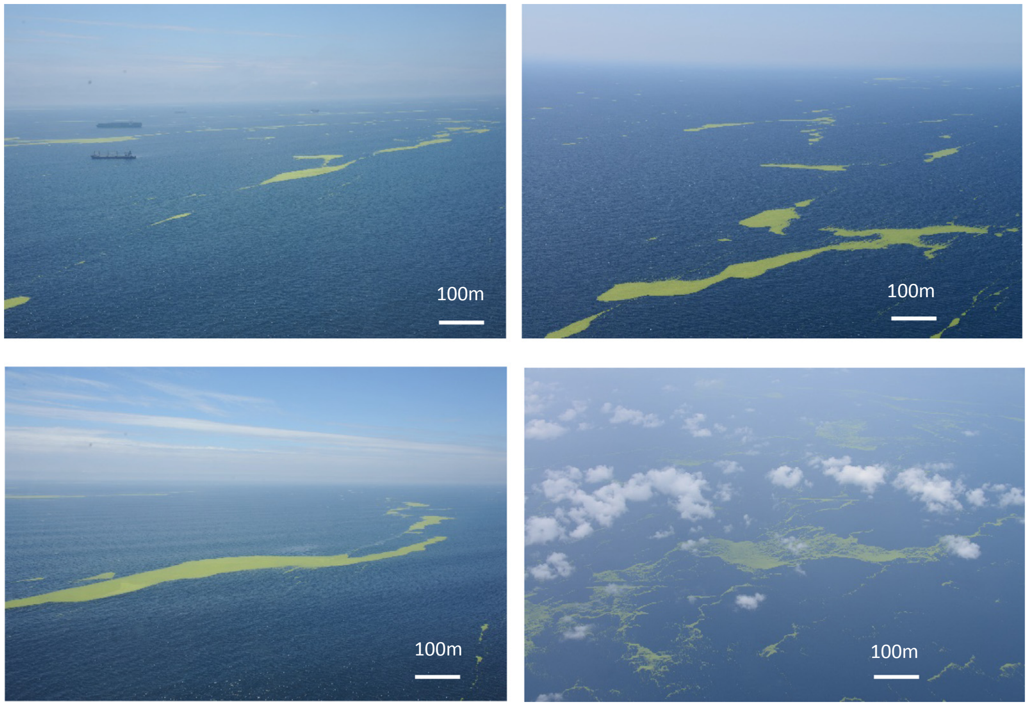

Fig. 1. Aerial photographs of the green macro-algal bloom in the Yellow Sea in June 2015.

Landsat TM and HJ-1 CCD) with the number of identified macro-algae pixels, the "total macro-algae coverage" in the whole image can be derived accordingly.

Indeed, the macro-algae are usually distributed as stripes (slicks) or patches with irregular shapes (see also Qiao et al., 2009; Gower et al., 2006; Hu et al., 2015, 2016), and they can rarely fully cover a satellite image pixel with tens (or hundreds) of meters spatial resolution. This scenario is clearly shown in the aerial photographs taken off Qingdao coast, in June 2015 (Fig. 1), when the macro-algae are well developed and its spatial coverage approaches the annual maximum in the Yellow Sea.

Under this circumstance, the macro-algae pixels identified in the satellite images are indeed mixed (not pure) and accordingly the estimated total macro-algae coverage is not accurate, unless the image spatial resolution (pixel size) is high (small) enough. Hu et al. (2010) estimates that the thin slicks visible in the MODIS images have only 2% actual macro-algae pixel coverage. Cui et al. (2012) further show that under the pure pixel assumption the MODIS derived total macro-algal coverage is significantly overestimated due to its coarse spatial resolution.

In order to address this issue and derive the accurate algae coverage, the linear pixel un-mixing approach has been applied to the satellite images with moderate and coarse resolution. Qi et al. (2016) derived the fractional algal coverage of each pixel by applying this method to the MODIS FAI images. And Xiao et al. (2017) proposed a new method to select the accurate "end member" (i.e. pure macro-algae and water pixels) from MODIS NDVI images. Yet until now, to our knowledge, the uncertainty of satellite derived total or actual/fractional macro-algae coverage estimates has not been rigorously assessed.

The objectives of this paper are, therefore, to (1) quantify the uncertainty of satellite derived total (fractional) macro-algae coverage without (with) the pixel un-mixing processing using the concurrent high-resolution (3-m) airborne Synthetic Aperture Radar (SAR) images; (2) develop a new method to correct the mixed pixel effect on the accurate determination of the macro-algal coverage from satellite images with moderate and low spatial resolution, and (3) obtain the accurate annual maxima of the green macro-algal coverage in the Yellow Sea during the past decade.

2. Data and methods

2.1. SAR images, processing, and macro-algal area extraction

Six airborne macro-algal bloom images were acquired by the SAR (X band, VV polarization) onboard ocean surveillance airplane in the western part of the Yellow Sea (near Qingdao city) during the period of June 28th to July 25th, 2015. Fig. 2 shows the spatial coverage of the images, and Table 1 lists the dates, lengths, and widths of each image. The spatial resolution of SAR images is 3-m. The width of the images is about 25-km, and the lengths range from 40-km to 134-km. The images are georeferenced using ENVI (The Environment for Visualizing Images) software to obtain the equal-area grids and de-noised using the Gamma filtering method.

As an example, Fig. 3a shows the SAR image for June 28th, 2015. In this figure, the stripes and patches with a higher brightness and irregular shape are the macro-algae floating on the sea surface (the black background). This effect is caused by the strong microwave backscattering of macro-algae (similar to the effect of land vegetation) (Shen et al., 2014). The floating macro-algae patches are differentiated from the ocean background (Fig. 3b), by setting a threshold which is determined through the histogram analysis of the image (e.g. Garcia et al., 2013; Gary et al., 2008). Specifically, the typical histogram for each macro-algae region of interest (ROI) in SAR image, follows the bimodal distribution (Fig. 3c), with the two peaks characterized by the macro-algae pixels and the ocean pixels, respectively. The threshold is determined as the middle of the vale between the two peaks which is 115 (in digital number) for the case shown in Fig. 3c (denoted by the red line). The total/fractional macro-algae coverage is then derived by multiplying the pixel size ($3 \times 3\text{-m}^2$) with the number of pixels that were identified as macro-algae.

There are three notes here. Firstly, for the high spatial resolution image with 3-m resolution, it is assumed that each pixel is pure, e.g. covered by either water or macro-algae (although sub-pixel issue may also exist to some extent); and the total macro-algae coverage area equals to the fractional macro-algae coverage. Secondly, the spatial resolution for each pixel in the georeferenced SAR image is the same (9-m^2), as the image is re-sampled during the georeference process and all