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Comparison of the efficacy of MODIS and MERIS data for detecting cyanobacterial blooms in the southern Caspian Sea

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ABSTRACT

Medium Resolution Imaging Spectrometer (MERIS) data, Moderate Resolution Imaging Spectroradiometer (MODIS) data, and hydro-biological measurements were used to detect two very severe blooms in the southern Caspian Sea in 2005 and 2010. The MERIS Cyanobacteria Index (CI_{MERIS}) was more reliable for detecting cyanobacterial blooms. The CI_{MERIS} and MODIS cyanobacteria indices (CI_{MODIS}) were compared in an effort to find a reliable method for detecting future blooms, as MERIS data were not available after April 2012. The CI_{MODIS} had a linear relationship with and similar spatial patterns to the CI_{MERIS}. On the CI_{MODIS} images, extremely high biomass cyanobacteria patches were masked. A comparison of classified in situ data with the CI_{MODIS} and Floating Algal Index (FAI) from four images of a severe bloom event in 2005 showed that the FAI is a reliable index for bloom detection over extremely dense patches. The corrected CI_{MODIS}, the MODIS FAI and in situ data are adequate tools for cyanobacterial bloom monitoring in the southern Caspian Sea.

1. Introduction

The Caspian Sea is the largest enclosed water basin on earth, with an area of 386,400 km^2 and 7250 km of coastline (Kostianoy and Kosarev, 2005). It is experiencing severe environmental threats, including water level fluctuations, over-fishing, poaching, invasive species, industrial, agricultural and urban pollution, and unsustainable development (de Mora and Turner, 2004a). The trophic state of the southern Caspian Sea has shifted from oligotrophic to meso-eutrophic over the last decade (Nasrollahzadeh et al., 2011). The phytoplankton biomass has increased with eutrophication, and some large, dense cyanophyte blooms have been observed in several regions of the Caspian Sea in recent years. A severe algal bloom occurred in the southern Caspian Sea in August 2005, affecting an area of 20,000 km^2 (Soloviev, 2005). A smaller algal bloom was subsequently observed in the coastal waters of Iran in October 2006 (Nasrollahzadeh et al., 2008). Anomalous algal blooms occurred repeatedly in the coastal waters of the southern Caspian Sea in the summers of 2007, 2009 and 2010 (Nasrollahzadeh et al., 2011). All bloom-producing algae in the southern Caspian Sea were members of the phylum Cyanophyta, i.e., cyanobacteria/blue-green algae (phycocyanin) (Nasrollahzadeh et al., 2008). The genus *Nodularia* was numerically dominant over other taxa of algae, forming more than 98% and 96% of phytoplankton abundance and biomass, respectively (Soloviev, 2005; Nasrollahzadeh et al., 2011).

Rantajärvi et al. (1998) demonstrated that water-sampling programs do not adequately report phytoplankton biomass distributions, particularly during bloom conditions when variability in phytoplankton density is high. Satellite remote sensing data have been recommended as an alternative, as they provide more reliable information about the distributions of cyanobacterial blooms (Kahru, 1997; Kahru et al., 2004; Kutser, 2004). Unlike other phytoplankton species, cyanobacteria can form surface scums in calm weather conditions and can therefore appear similar to land-surface vegetation (Paerl and Ustach, 1982; Sellner, 1997; Da Rosa et al., 2005). Therefore, the Normalized Difference Vegetation Index (NDVI) and/or Enhanced Vegetation Index (EVI) can detect intense surface cyanobacteria blooms (Chen and Dai, 2008; Xu et al., 2008). Additionally, the presence of phycocyanin can be detected from spectral reflectance (Dekker et al., 1991; Gons et al., 1992; Jupp et al., 1994). There have been several attempts to monitor and delineate cyanobacterial blooms using satellite data (Kahru, 1997; Ruiz-Verdú et al., 2008; Kutser, 2004; Reinart and Kutser, 2006; Kutser et al., 2006; Becker et al., 2009; Wheeler et al., 2012; Hu, 2009; Budd et al., 2001; Wynne et al., 2010; Vincent et al., 2004). Multispectral satellite sensors, such as Landsat TM (Vincent et al., 2004; Chang et al., 2004), Landsat ETM$^+$ (Torbick et al., 2008), DigitalGlobe's QuickBird (Wheeler

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et al., 2012) and hyperspectral satellite sensors, such as Hyperion (Kutser, 2004), have been used for the quantitative mapping of cyanobacteria during blooms. The spatial and temporal coverage of these sensors do not make them amenable to the regular monitoring of potential cyanobacterial blooms. Indeed, over the last three decades, there have been significant advances in technology and algorithm development, allowing satellite ocean color sensors (such as MODIS, SeaWiFS and MERIS) to be used for studying cyanobacterial blooms (Reinart and Kutser, 2006; Kahru et al., 2004,2007; Kutser et al., 2006,2006; Becker et al., 2009; Wheeler et al., 2012; Hu et al., 2010; Hu, 2009; Xiu-Zhen et al., 2008).

Images from the Medium Resolution Imaging Spectrometer (MERIS) have been widely used to monitor cyanobacterial blooms, even in water with suspended sediments (Kutser et al., 2006; Ruiz-Verdú et al., 2008; Wynne et al., 2008, 2010; Wheeler et al., 2012). MERIS has several spectral bands in the red and near infrared that allow spectral shape algorithms to target severe blooms (Gower et al., 2005; Wynne et al., 2008). Spectral shape methods use a computational equivalent of the second derivative (Wynne et al., 2010). Forms of these computations for MERIS data include Fluorescence Line Height (FLH) (Gower et al., 1999), the Maximum Chlorophyll Index (MCI) (Gower et al., 2005) and the Cyanobacteria Index (CI) (Wynne et al., 2008). The MCI has been effectively used for monitoring blooms in coastal oceans (Gower et al., 2005) and lakes (Binding et al., 2011, 2013). The CI, which is the negative of the FLH (Gower et al., 1999), has been very effective for identifying cyanobacterial blooms in Lake Erie (Wynne et al., 2008,2010), and it appears to be less sensitive to high sediment loads than the MCI (Stumpf et al., 2012).

The Moderate Resolution Imaging Spectroradiometer (MODIS) has bands similar to MERIS, centered at 678 nm, which may allow for the application of an equivalent algorithm. Xiu-Zhen et al. (2008) hypothesized that chlorophyll mainly relies on algal cells for photosynthesis; algal cells have spectra with an absorption peak near 440 nm, a reflection peak near 550 nm, and a fluorescence peak near 683 nm. Considering these factors, they introduced an index based on the characteristics of MODIS 250 and 500 m bands for mapping cyanobacteria blooms. Hu (2009) developed a novel ocean color index, the Floating Algae Index (FAI), and used it to detect floating algae in open ocean environments using medium-resolution (250 and 500 m) data from MODIS. The FAI is immune to atmospheric, water and sediment constituent interference for case-2 waters. It also has advantages over NDVI and EVI (Hu, 2009). Although the FAI was designed to detect floating algae in open oceans, it may be useful for deriving bloom patterns in lakes (Hu, 2009). Wynne et al. (2013) analyzed the CI for MODIS data following Wynne et al. (2010) and concluded that the CI_{MODIS} identifies the same blooms detected with CI_{MERIS}, with similar spatial patterns. With the loss of MERIS data availability on April 2012, MODIS data were used to build on the MERIS-based dataset.

The efficacy of MCI, CI and FAI methods in detecting intense cyanobacteria blooms in the open ocean and in inland lakes has been investigated. To date, these methods have not been proposed for detecting surface cyanobacterial blooms in the Caspian Sea, which exhibits physical and biological characteristics common to both seas and lakes (Aladin et al., 2001). The Caspian Sea is not a homogeneous lake, and three different water bodies are united within its borders, each with its own physical conditions and biological diversity. The distinct differences in the physical conditions of the three water bodies have resulted in differences in biodiversity. Unlike other lakes, the Caspian Sea is not freshwater but brackish (Kostianoy and Kosarev, 2005). However, the water of the Caspian Sea contains three times less salt than that of the ocean (de Mora et al., 2004b). Thus, each of the four areas of the Caspian Sea, i.e., the northern, middle and southern regions and the Kara-Bogaz-Gol gulf, has distinct physical features.

2. Materials and methods

2.1. Field data

Two marine sampling trips were conducted by the Iranian Fisheries Research and Training Organization (IFTRO) in the southern Caspian Sea between August and October 2005 and between August and September 2010 on non-consecutive days (Fig. 1). Temperature, salinity, pH and dissolved oxygen measurements were collected from the water surface to the maximum depth using a CTD model Ocean-Seven. In a previous study, surface water samples were collected at a depth of 1 m at each station using a 1.6-L Ruttner sampler (Vollenweider et al., 1974) and returned to the laboratory within six hours of collection. Nutrient concentrations were analyzed with a Shimadzu UV-1602 spectrophotometer. Nitrate and nitrite concentrations were determined using a reduction column and the standard pink azo dye method. Ammonia concentration was determined via the hypo-phenol oxidation-blue dye method (DIN = NO^{2-}, NO^{3-} and NH^{4+}). Phosphate (DIP) and silicate (DSi) were determined by the standard molybdenum blue and yellow method, as suggested by APHA (2005). The digestion of samples for the determination of total nitrogen (TN) and total phosphorus (TP) was completed following the persulfate digestion procedure of Valderrama (1981). Chlorophyll-*a* was determined fluorometrically following Welschmeyer (1994). Phycocyanin concentrations were estimated fluorometrically using a modification of the method proposed by Abalde et al. (1998) and Siegelman and Kycia (1978). Phycocyanin was extracted by freezing the samples at −21 °C and thawing at 4 °C three times in phosphate buffer (pH = 6.8) under dim light. The extract was clarified by centrifugation at 22,000*g* for 15 min, and the phycocyanin concentration in the supernatant was determined by a fluorometer equipped with a 577-nm band-pass excitation filter and a 660-nm cutoff emission (Konopko, 2007). The detection limit for this fluorometric method was 0.22 $\mu g\ L^{-1}$.

2.2. Satellite data

Ocean color satellite data were used in this study. MODIS Aqua Level-1A data (for the 5th, 7th of August 2010; the 16th, 18th, 24th of August 2005 and the 1st of September 2005) were obtained from the GODDARD Space Flight Center. MERIS Level-2 (L2; atmospherically corrected water-leaving radiance reflectance) data were acquired from the European Space Agency (ESA) (for the 10th, 16th, and 19th of August and 1st of September 2005; and the 4th and 7th of August 2010). Frequent cloud cover over the Caspian Sea hindered the acquisition of adequate satellite images. The clearest cloud-free satellite images were chosen for comparison and validation with field data. Images were visualized and analyzed using NASA SeaDas 6.4 and Envisat's BEAM 4.11 software. To reduce speckling noise from the satellite images, a median value from a 3 × 3 box was used to smooth the image data spatially (Hu et al., 2001).

2.3. Satellite image processing

MODIS data were processed using NASA SeaDAS 6.4. Atmospheric corrections were made using the iterative approach for sediment-rich waters (Stumpf et al., 2003). Gordon and Wang (1994) algorithm was used to correct for atmospheric interference in the six ocean color bands in turbid coastal waters to obtain the water-leaving radiance, $L_w(\lambda)$ (Arnone et al., 1998; Stumpf et al., 2003). Then, the OC4 band-ratio algorithm was used to estimate chlorophyll-*a* concentrations in mg m^{-3} (O'Reilly et al., 2000).

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