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Algal blooms detection in Colombian Caribbean Sea using MODIS imagery

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ABSTRACT

The current capacity in the Caribbean region to enhance the knowledge about algal blooms and harmful algal blooms has several logistical constraints. This work aimed to explore the detection of possible algal blooms using Moderate Resolution Imaging Spectroradiometer (MODIS) Fluorescence Line Height (FLH) data in the Colombian Caribbean Sea between 2003 and 2013. Monthly FLH images with 4 km of spatial resolution were processed and classified. The relationship between the Sea Surface Temperature (SST) and the FLH were explored using a Geographically Weighted Regression. The results showed three areas identified as having possible persistent blooms: the Urabá Gulf (UG), Magdalena Rivermouth (MRM), and Guajira Peninsula (GP). The SST does not have any considerable influence on the variation in the FLH. The supply of nutrients during the rainy season may be causing the frequent massive algae growth. MODIS fluorescence was useful as a screening tool to identify risk areas for potential algal blooms.

1. Introduction

Algal blooms are accumulations of phytoplankton, with the growth of one or more species which leads to an increase in the biomass. This occurrence is being reported increasingly along the coastal areas of all the continents (Richardson, 1997; Lewitus et al., 2012; Anderson et al., 2015). The algal blooms can be harmless; on the positive side, they indicate areas of high biological productivity. On the negative side, however, they are harmful (due to reduced oxygen) or toxic. In recent years, more attention has been focused on the negative impacts of the denominated harmful algal blooms (HABs) (Sellner and Doucette, 2003). These HABs can produce toxins, resulting in various negative impacts such as increased mortality of organisms (fish, birds, and mammals), public health problems in beaches and coastal areas, and economic losses in activities such as fishing and tourism (Scholin et al., 2000; Ahn et al., 2006; Lewitus et al., 2012; Busch et al., 2013).

The global distribution of algal blooms and HABs reports have increased significantly in recent decades (Glibert et al., 2005). Some studies attribute the overall increase in the spatial distribution of algal blooms and HABs to the changes in ocean currents, environmental conditions, and anthropogenic factors such as coastal eutrophication, physical disturbance of coastal regimes, and transport of invasive species in ships' ballast waters (Smayda, 1997; Anderson et al., 2015).

Another important causal factor is climate change. The increase in temperature favors growth of some algal blooms and HABs-causing organisms, such as cyanobacteria, which grow best at higher temperatures (often above 25 °C) than the other phytoplankton species, such as diatoms and green algae (Paerl et al., 2001). Increasing global temperature also affects rainfall patterns and drought, intensifying rains and increasing nutrient discharge into water bodies, thus promoting the formation of algal blooms and HABs (Glibert, 2013).

To study the effect of climate change on the dynamics of HABs, several approaches have been applied. One of the approaches to studying this issue is the application of satellite remote sensing, which has become a useful tool, along with in situ monitoring, which provides near real-time information on a broad spatial and temporal scale for the study of marine and freshwater ecosystems (Trescott, 2012). Satellite ocean color sensors like Coastal Zone Color Scanner (CZCS), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), and Medium Resolution Imaging Spectrometer (MERIS) have been very useful for the construction of algorithms for the detection, mapping, and monitoring of algal blooms and HABs (Richardson, 1997; Hu et al., 2005; Frolov et al., 2013; Blondeau-Patissier et al., 2014).

The chlorophyll-a pigment (Chl-a) is a universal index of phytoplankton biomass. Information on this pigment in the oceans has been obtained from its absorption properties for many decades (Lorenzen, 1966). This is used as an indicator for the location and movement of

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algae blooms and the detection of HABs although this pigment alone cannot differentiate between microalgae species (Stumpf et al., 2003; Busch et al., 2013).

However, Chl-a values are often biased in optically complex waters that have a high diversity of dissolved components, such as coastal waters. In these cases, the Chl-a measurements can be overestimated due to the abundance of CDOM (Colored Dissolved Organic Matter) or concentrations of matter in suspension that interfere with the signal captured by the satellite sensor (Tang et al., 2003; Ahn et al., 2006).

Fluorescence algorithms have significant advantages in the estimation of Chl-a in optically complex waters and areas where HABs occur. The fluorescence signal, when present, is attributed solely to photosynthetic activity, so it is unlikely to be confused with any other signal, such as CDOM or suspended matter (Xing et al., 2007). Thus, making the satellite-derived Chl-a estimate using fluorescence is more robust to detect high biomass events. Although fluorescence does not provide the level of specificity necessary to identify HABs, it does provide a reasonable approximation for understanding the dynamics of algal blooms and provides a first-order estimate of the spatial and temporal scales needed to monitor the algal blooms in the coastal ocean (Frolov et al., 2013).

In Colombia algal blooms and HABs have been reported for the past 40 years, both in the Pacific and Caribbean coasts, with a higher number of reports concerning the latter, some with adverse effects such as fish mortality and human poisoning (Mancera and Vidal, 1994; Mancera and Vidal, 2007; Mancera Pineda et al., 2009; García-Hansen et al., 2004). The use of satellite data for the study of algal blooms in Colombia is scarce (Selvaraj et al., 2009). Piedrahíta et al. (2013) used data from FLH to detect algal blooms in the Colombian Pacific Ocean; however, no studies were found in the Colombian Caribbean Sea related to the application of satellite imagery for the detection and study of the dynamics of algal blooms in space and time and their relationship with environmental variables. The need to develop systematic and integrated monitoring systems has been recognized recently (Mancera Pineda et al., 2009). Due to the geographical position and environmental attributes, the Colombian Caribbean offers important services to the transportation, fishing, and tourism industries. Therefore, any phenomenon that affects these activities will bring about negative economic consequences in the region. However, the massive extension of the area and the complexity of HABs make monitoring and comprehensive research programs challenging to conduct. Given this situation, the need to generate early warning systems and efficient monitoring methods arises. In order to seek ways to attain this goal, the aim of this paper is to explore the usefulness of MODIS fluorescence imagery to 1. detect possible algal blooms and HABs in the Colombian Caribbean waters and 2. evaluate the relationship of sea surface temperature (SST) and FLH.

2. Materials and methods

2.1. Study area

The Colombian Caribbean Sea with its Exclusive Economic Zone (EEZ) is located within the Caribbean Basin (Fig. 1). The Colombian Caribbean coast covers a wide latitudinal range, spanning between 8° N to 13° N, from the boundary with Panama in the southwest (SW) at longitude 79° W, till the high Guajira in the northeast (NE) at longitude 71° W (Bernal et al., 2006). The Colombian Caribbean coast is characterized by its upwelling, primarily driven by the trade winds, which are strongly evident in the coast of the peninsula of La Guajira (Andrade and Barton, 2005). In this region, the climate system is considered as being dependent on the trade winds from the northwest as well as the oscillations of the Intertropical Convergence Zone (ICZ). In this coast, there are two surface wind jets that are opposite in their direction – the surface stream of San Andrés and the surface jet of Chocó. The dry season in the Colombian Caribbean is from December to April, and the wet season occurs through the rest of the year, interrupted by a relative reduction in July and August, popularly known as the "Veranillo de San Juan" (Mesa et al., 1997; Bernal et al., 2006).

On the Caribbean coast, the rainiest month of the year is October, and the driest ones are February and March; however, there is a significant spatial variation in terms of rainfall. The southwest area, which is closer latitudinally to the jet of Chocó, is a very humid region (the Urabá Gulf has an average annual rainfall of 4300 mm), and it transitions into a desert region in the northwest (the Guajira, with an average annual rainfall of 460 mm) (Mesa et al., 1997; Bernal et al., 2006). The rivers that discharge into the Colombian Caribbean include the Magdalena River, the Atrato River, the Sinu River, and the Rancheria River with average flows of 7200 m^3/s, 4900 m^3/s, 376 m^3/s, and 7.8 m^3/s, respectively (IDEAM, 2013).

The Caribbean Sea is considered as an oligotrophic region (Müller-Karger et al., 1989). The low biological productivity of the open areas is mainly due to the strong thermal stratification that hinders the entry of nutrients into the photic layer; however, more fertile and productive zones can be found in the coastal areas (Margalef, 1969; Corredor 1977 in Melo et al., 1995). When talking about the general circulation of the Colombian Caribbean Sea, the Caribbean current the center of uprisings in the Guajira and the cyclonic turn of Panama, located in the Gulf of Darien stands out (Bernal et al., 2006). The Darien has been considered as comprising the coastal portion of the cyclonic gyre of Panama – Colombia. In Guajira, the countercurrent is submerged, and it becomes a subsurface current under the center of the upwelling with a core with its maximum velocity at a 200 m depth. The dynamics of the countercurrent - the subsurface current is controlled mainly by the wind. During the time when the trade winds of the northeast are the strongest, the upwelling of the Guajira is at its maximum, and the countercurrent is sub-superficial. In the wet season, the opposite takes place, and the countercurrent manifests on the surface throughout the Colombian Caribbean coast (Andrade and Barton, 2000; Andrade and Barton, 2005).

2.2. Algal bloom detection

We used 11 yearly and 132 monthly images of Normalized Fluorescence Line Height (FLH), level 3, taken between 2003 and 2013 by the Aqua satellite of the MODIS sensor board (https://oceancolor.gsfc.nasa.gov/cgi/l3), which was operated by the National Aeronautics and Space Administration (NASA) with a spatial resolution of 4 km. The images were processed using the ArcGIS version 10.4, extracting data per pixel, and reclassified using the specifications prescribed by Hu et al. (2005) in the following intervals:

0 to 0.0299 $W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$
0.0299 to 0.04 $W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$
0.04 $W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$ – Maximum value in each image

The classification was carried out in order to detect areas with FLH $>$ 0.04 $W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$. According to Hu et al. (2005), areas with those levels of FLH have shown excellent results with regard to the detection and monitoring of HABs, particularly the dinoflagellate *Karenia brevis*.

The areas with FLH $>$ 0.04 $W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$ were calculated as possible areas having algal blooms. Normality tests were carried out using Kolmogorov-Smirnov and Shapiro Wilk tests. Comparisons between the monthly and annual variation were performed through an analysis of variance (ANOVA) (SPSS V. 20), and the post-ANOVA Tukey test was carried for the cases in which significant differences were founded. The locations with the highest values were recognized to identify areas with more significant presence of possible algal blooms.