SEASONAL VARIABILITY OF CHLOROPHYLL A AND SEA SURFACE TEMPERATURE OBTAINED WITH THE SEA-VIEWING WIDE-FIELD OF VIEW SENSOR AND THE MODERATE RESOLUTION IMAGING SPECTRORADIOMETER EOS PM IN WATERS OFF MAGDALENA STATE, COLOMBIAN CARIBBEAN 1997-2006

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The productive characteristics of the Magdalena waters are unknown because of a lack of studies that evaluate its biological, chemical and physical dynamics. In this study, remote chlorophyll *a* concentration and sea surface temperature data were obtained (SeaWiFS and MODIS Aqua sensors) and analyzed to compare the potential production of seasonal continental discharges and upwelling over time. A temporal thermal and Chlorophyll *a* stability was found, indicating that the water capability to enhance phytoplanktonic development remained unaffected. No thermal differences were found between sectors, while the higher Chlorophyll *a* of the southwestern coastal waters defined them as mesotrophic, opposite to the oligotrophic waters of the coastal northeastern sector and the oceanic sectors. Continental runoff is the most powerful event that controls the phytoplanktonic development, especially in the western extreme during wet seasons. Contrary, upwelling events play a more important role in the water fertilization only far in the eastern extreme, when the continental discharges are low.

1. INTRODUCTION

The Colombian Caribbean is known because of the presence of two relatively important upwelling systems which are highly seasonal. One of the former was reported in the Guajira Peninsula, while the other was located in the waters of the Magdalena State, in front of Punta Aguja [4]. However, the productive characteristics of this system contrasted to the influence of other local events, such as continental runoff, have not been well described because of a lack of a full biological, chemical and physical oceanographic description of the Magdalena State waters over time.

2. METHODS

2.1. *Study area.*

The study area was comprised between 74º 00´ and 75º 00´ W and between 10º 59´ and 12º 00´ N, totalizing an area of 12,553.8602 km^2. The weather in the Magdalena Region obeys to the general climatic pattern of the Caribbean and depends on macroscale phenomena such as the presence or absence of Trade Winds and the latitudinal displacement of the Intertropical Convergence Zone (ITCZ) [1]. Throughout the year, it has been commonly observed that there are four seasons: major dry (December-April), minor wet (May-June), minor dry (July-August) and major wet (September-November) [6]. With regards to the continental runoff features of the study area, the mouth of the Magdalena River (most important Colombian river) can be found in the southwestern extreme. Further east is located the Ciénaga Grande de Santa Marta (CGSM), which lead to the sea in La Boca de la Barra. The continental shelf in this sector is wide and shallow because of the absence of the Sierra Nevada de Santa Marta (SNSM) foothills, contrary to what happens more towards northeast, where the inclination of the continental shelf becomes high. This part of the Magdalena coastline is characterized by the presence of several bays and inlets, among which are the Gaira inlet, Santa Marta Bay and the different bays located in the Tayrona National Natural Park (PNNT), where minor rivers, such as the Gaira and Piedras Rivers, have seasonal influence [7].

In order to compare the potential of atmospheric and oceanographic events such as upwelling and continental runoffs that occur during the dry and wet seasons in the Magdalena State, Colombian Caribbean, as agents that stimulate the development of primary producers, monthly average 16 km^2 satellite data and images of the sea surface temperature (SST) (Moderate Resolution Imaging Spectroradiometer EOS PM -MODIS Aqua-) and Chlorophyll *a* (Chl *a*) concentration (Sea-viewing Wide-Field-of-view Sensor -SeaWiFS-) were obtained, processed and interpreted between July 2002 and September 2006 as well as between September 1997 and 2006, respectively.

The use of remote sensing to study coastal and oceanic ecosystems in the Caribbean is not well developed in the country and is just until recently more widely applied, despite of its high applicability and reliability in the understanding of its oceanographic dynamics in both a large temporal and spatial scale. A large spatial and temporal scale analysis, which could be suited using remote sensing data, was therefore required in order to validate or contradict the upwelling in the study area as important in the potential productivity of the Magdalena Region compared to events of continental water runoff.

The satellite data was provided by the Universidad Autónoma de Baja California in Mexico, where the first phases of processing were conducted using ENVI 4.3®, which implement the basic commands of the software SeaDAS®, that was then used to complete the processing and obtaining of the data and images.

Because of the high spatial variability of land and water characteristics of the study area, it was necessary to divide it into three coastal zones denominated Salamanca Gulf (GSLM), Gaira Inlet and Santa Marta Bay (EGBSM) as well as Tayrona National Natural Park (PNNT) and three oceanic sectors, which were located in front of the respective coastal zones, designated as OCEAN 1, 2 y 3 (Fig. 1). Each sector has different oceanographic characteristics, coastal relief and continental discharges and therefore, with the division of the study area, it could be observed how its ocean-atmospheric dynamics varied both spatially and temporarily.

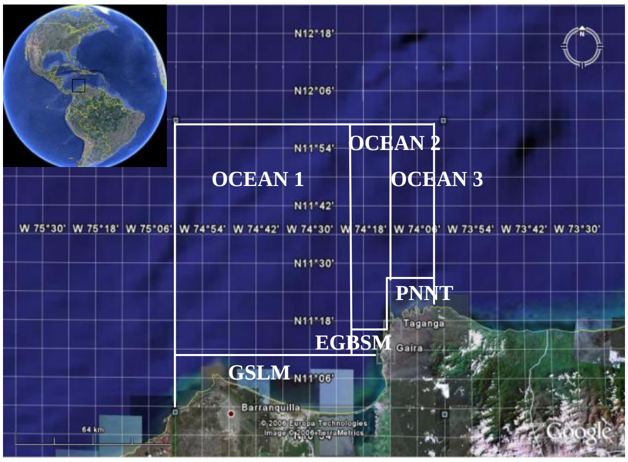

Figure 1. Study area off to the Magdalena State located between the 10´59´´ N – 12´00´´ N and the 74´00´´ W – 75´00´´ W. Sectors: Salamanca Gulf (GSLM), Gaira Inlet and Santa Marta Bay (EGBSM), Tayrona National Natural Park (PNNT) and oceanic sectors (OCEAN 1, 2 y 3). Modified from [8].

Some meteorological and oceanographic variables such as the monthly average air temperature, precipitation levels, wind speed and Ekman´s depth were considered together with the remote SST data so as to determine the duration of each major and minor dry and wet season during the study decade in order to relate them to the phytoplankton biomass. It was observed that the seasonality is highly variable, with a non fixed length of each season (contrary to what was generally thought), due to the differences in the intensity and duration of macroscale and mesoscale climate patterns in which winds and precipitation levels play an important role. Hydrographic variables such as the levels of the Magdalena, Gaira and Piedras Rivers, which flow into GSLM, EGBSM and PNNT, respectively, and the topography, including the extension and inclination of the continental shelf, were also included in this work.

3. RESULTS AND DISCUSSION

Parametric and nonparametric statistical tests (ANOVA and Kruskal-Wallis; $p>0.05$) using the average values showed no significant differences with regards to the SST, which indicates that there was both a spatial (between sectors) and temporary (between years) thermal stability. Nevertheless, decreases in the magnitudes of the SST during months of dry seasons, in which it is more plausible to find the occurrence of upwelling events, were evidenced and this agrees with the conditions observed in other upwelling regions [5]. Additionally, it was found that during those seasons the wind velocity, Ekman´s potential depth and air temperature were high, and the precipitation levels were low, whereas during wet seasons contrary conditions were observed because of the displacement of the ITCZ above of the study area. This fact correlates with a lower continental runoff of the Magdalena, Gaira and Piedras Rivers in GSLM, EGBSM and PNNT throughout the first months of each year, which were commonly included in the mayor dry seasons, with increasing values during the last months, when the precipitation levels are much higher.

Regarding to the phytoplanktonic biomass spatial analysis, the results registered during all the seasons in the sector GSLM enabled to characterize this waters as mesotrophic, finding significantly higher values than those found in EGBSM, which were, in turn, higher than those evidenced in PNNT and the oceanic zones (ANOVA and Tukey HSD tests; $p<0.05$), sectors in which the water characteristics define them as oligotrophic. The high continental discharges in the southwestern extreme of the study area (primordially in the sectors GSLM and OCEAN 1 but also in EGBSM and OCEAN 2) by the Magdalena River and the CGSM during the whole year, were the ones that mostly determined the potential of the aquatic system to enhance the phytoplanktonic development, because they provide the marine water with alloctonous phytoplankton and apparently with a higher nutrient concentration compared to upwelling events in this area [9]. Nevertheless, with the discharges of the rivers, the concentration of the substances with similar spectral characteristics to Chl *a*, also increases, and the overall effect is to overestimate the values of this satellite variable principally during months of wet seasons [10]. Moreover, it has been previously found that when the nutrient input is not continuous, which is the case of the upwelling events in the Magdalena Region, the phytoplanktonic cells consume fast the provided nutrients and tend to submerge in the lower water layers [3] in which the SeaWiFS remote sensor cannot take measurements of the phytoplanktonic biomass [2]. Therefore, it is possible that the differences of Chl *a* found between the coastal southwestern extreme of the study area and in the PNNT sector were not as prominent as it was showed by the satellite data analysis, given the fact that in PNNT the fertilization due to upwelling events is more important compared to GSLM and EGBSM sectors and consequently, a higher concentration of phytoplanktonic cells, which, as a result, would have been underestimated, could have been found in water layers below the 10 m in the former mentioned sector. The higher importance of the upwelling systems as a fertilization source in PNNT and in OCEAN 3 is due to the lower continental influence in this areas and because both the winds and the continental shelf have appropriate characteristics to enhance a more continuous and intense ascending movement of the submerged waters during the months of dry seasons. The later statement can be evidenced in the satellite image of November of the year 1998 that corresponds to a major dry season. A north-west displacement of the Chl *a* was observed, which is explained with the presence of intense Trade winds that are typical of this season. Because of the highly abnormal rainfall in this year, the continental water inputs were also important and this explains the red, yellow and orange colorations in GSLM and EGBSM and greenish in PNNT and the ocean sectors (Fig. 2).

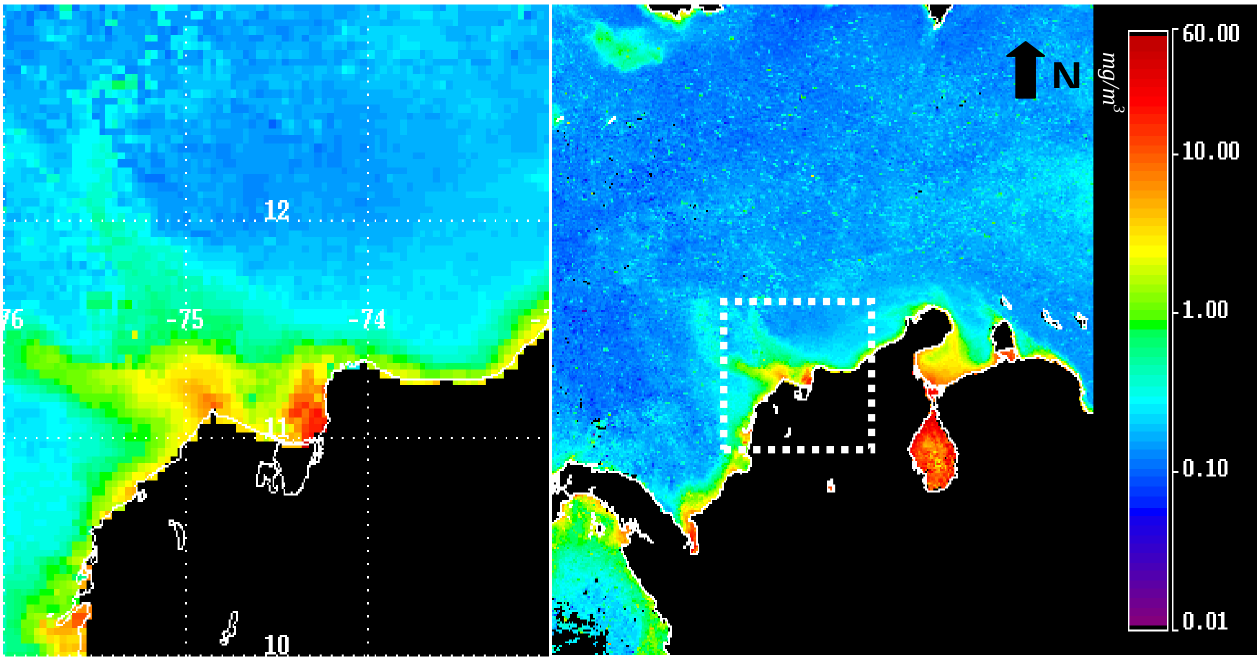

Figure 2. Satellite image of the Chl a concentration (mg/m³) corresponding to November 1998 and obtained with the SeaWiFS remote sensor.

On the other hand, no statistical temporal differences (between years) were found in the average Chl *a* values (Kruskal Wallis test; $p>0.05$), concluding that even though events such as El Niño Southern Oscillation occurred, the overall capacity of the system to enhance the development of primary producers has not be modified. In general, higher Chl *a* concentrations were found during months of wet seasons as opposed to dry seasons, which agrees with the higher levels of the Magdalena, Gaira and Piedras Rivers in the final months of each year. This fact corroborates the importance of the continental influence in the fertilization of waters and development of the primary producers, comparatively with the upwelling systems that are present in the Magdalena State.

4. CONCLUSIONS

It was found that there was both a thermal spatial and temporal stability, whereas with regards to the Chl *a* biomass, it evidently changed in the different sectors of the study area primarily because of the distinct continental water runoff characteristics, which determined the potential of the development of primary producers, especially in the sectors located more to the west of the study area. Far in the eastern side, the upwelling events played a more important role in the fertilization of these waters, because of the lower continental discharges and the better topographic characteristics of the continental shelf.

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