TURBIDITY PATTERNS AND CLIMATE VARIABILITY IN THE GUADALQUIVIR ESTUARY (SW IBERIAN PENINSULA)

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ABSTRACT

During the last years, an increase in the intensity and frequency of floods in the SW of the Iberian Peninsula has occurred due to the storms rise. These phenomena coincide with negative North Atlantic Oscillation (NAO) phases, presenting a clear significant relationship between the climatic pattern that dominates the index variation and the flood events in the region. The pronounced episodes of rainfall intensify the rivers discharge and favour the input of nutrients and suspended particulate matter in the continental shelf. The role of these rivers in the fertilization of the coastal area of the Gulf of Cadiz, mostly influenced by the Guadalquivir estuary, constitutes the major factor determining the productivity of the basin, from phytoplankton to fisheries resources as anchovy. Accordingly, the appearance of the turbidity events in the Guadalquivir mouth has a relevant impact on rates of primary production over the adjacent coastal region and on several socio-economic strategic activities such as aquaculture, fishing, tourism, navigation, etc. The mail goal of this study is to analyze the spatial and temporal variability of the river turbidity plume in connection with the meteorological and oceanographic processes controlling it. To achieve this aim, we have processed Moderate Resolution Imaging Spectroradiometer (MODIS) level L2 images covering a period of 8 years (2003-2010). In addition, several buoys have been deployed to measure biogeochemical parameters as temperature, salinity, chlorophyll, fluorescence and turbidity and a meteorological station located in the river mouth. The first preliminary results confirm that the appearance of the estuarine plume is associated with the increment in river discharge (negative NAO) during the rainy seasons and with tides and wind dynamic throughout the dry seasons. Therefore, these relationships between turbidity patterns and climate indices will improve the characterization of the Guadalquivir complicated system in the quantification of the primary production under scenarios of global change. We have developed an approach to successfully map turbidity in the estuary, and to understand the phenomena that control the exchange of riverine material with the coastal region. Thus, the incorporation of the MODIS synoptic observations as a valuable tool for operational monitoring of water quality is recommended and would benefit the knowledge of both physical oceanography and marine biology components in the Gulf of Cadiz.

INTRODUCTION

The Gulf of Cadiz is a wide basin located on the SW coast of the Iberian Peninsula near to where the Atlantic Ocean connects to the Mediterranean Sea through the Strait of Gibraltar. The continental shelf from the east of Cape Santa Maria to the west of the Bay of Cadiz has a broad width (around 50km) and receives substantial fluvial inputs associated with the discharge of major rivers such as the Guadiana, the Guadalquivir and the Tinto–Odiel (Figure 1). The Guadalquivir estuary is a well-mixed mesotidal system with a longitudinal salinity gradient (1). The present zone is enclosed by the spits of Doñana and La Algaida, inland of which there is a large area of freshwater marshland of 140,000 ha. (2). The tidal influence extends up the Guadalquivir as far as the Alcalá del Río dam (3), 110 km upstream from the river mouth at Sanlucar de Barrameda. The maximum tidal range for the Guadalquivir mouth is 3.86 m (2). The river between Sanlucar de Barrameda and Seville is unique, being the only navigable river in Spain. Moreover, the estuary has undergone substantial rapid agricultural, fisheries, and anthropogenic development, particularly in recent

decades (4). The estuary and its coastal fringe are characterized by high current velocities (5), large loading of suspended matter and high turbidity levels (6), and high biological productivity (7).
In spite of the social and economic importance, until very recently, only a few studies have been conducted on the zone. Water clarity and quality are important for the functioning of the ecosystems of the estuary and adjacent area, acting as an indicator of nutrient loading and sediment dynamics, and are critical variables for seagrass growth. The region is characterized by a strong seasonality together with important synoptic weather events (8) that largely control chlorophyll concentrations and suspended material. Management strategies and methods that facilitate monitoring of estuaries are required, particularly over synoptic scales. Satellite-borne sensors technology is becoming an ideal tool for assessing turbidity and chlorophyll, thus enabling a more effective and reliable analysis of the temporal and spatial dynamics of turbid plumes having the potential for improving our understanding of nearshore processes (9). The ocean color of the Guadalquivir estuary is affected by a variety of processes typical of environments with Case-II waters (i.e., the optical properties do not co-vary), including phytoplankton blooms, sediment plumes, and other episodic phenomena, such as runoff events. Each of these processes can individually modulate satellite-detectable signals contributing to the overall variability, especially in these waters which are characterized by a variety of seasonally-varying circulation patterns (8).

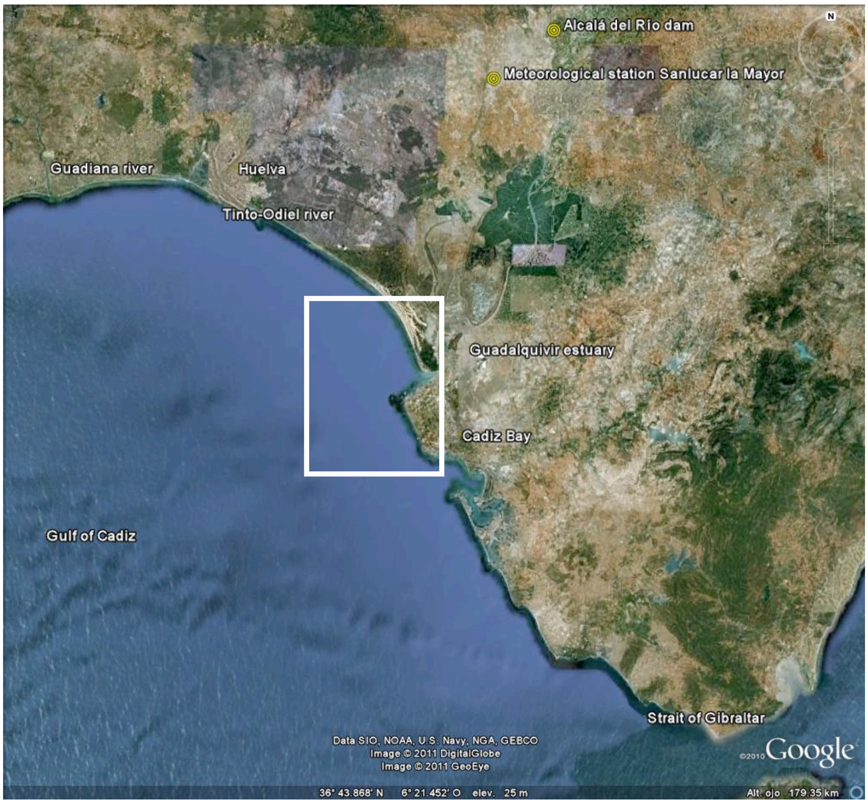

Figure 1. Location of the Gulf of Cadiz coastal area and the Guadalquivir estuary. White rectangle delimits the Region of Interest (ROI) (Google Earth copyright).

The aim of this study is to assess the potential of Ocean Color MODIS images for deriving water-quality parameters, and to develop an approach for monitoring and predicting turbidity and phytoplankton blooms in the Guadalquivir estuary and adjacent coast. This paper presents results of the remotely-sensed observations for better characterizing the seasonal and interannual variability of the river plume and its influence on chlorophyll patterns. Here we focus on analyzing the role of different meteorological forcing factors responsible for plume dynamics with the object of significantly improving our understanding and stimulating future studies. The incorporation of satellite-derived products in the proposed approach should make it a valuable and powerful tool for investigating and managing coastal and transition waters, and should provide predictions of outcomes relevant for policy-makers and government agencies. A more general benefit expected of this work would be improved knowledge of both physical oceanography and marine biology with wide operational applications in coastal research.

METHODS

Satellite ocean color images were obtained from the NASA Moderate Resolution Imaging Spectroradiometers (MODIS) on the Aqua multispectral platform. All available optical measurements of chlorophyll (Chl) and Remote Sensing Reflectance at 555 nm (Rrs555), both level L2 at medium spatial resolution (1 km), covering the region of interest and spanning the years from 2003 to 2010 were ordered and downloaded via-ftp from the Ocean Color Website (http://oceancolor.gsfc.nasa.gov). These data were processed to Level 2 geophysical products by NASA using default coefficients and community-standard algorithms. SeaDAS image analysis software (SeaWiFS Data Analysis System, version 6.2; http://seadas.gsfc.nasa.gov) was used to read and remap the data to a Mercator projection at 1km resolution. On downloading MODIS data to a local system, the data were displayed to assess image quality. As the data are processed, checks are made for different defined conditions. We used the standard SeaDAS algorithm with the ‘‘land’’ and ‘‘cloud’’ flags to remove the data unintentionally interpolated among others applied as masks with L2_flags. These additional and relevant quality control tests correspond to "Atmfail", "Higlint", "Hilt", "Hisatzen", "Hisolzen", "Lowlw", and "Chlfail". These generated data files were edited and analyzed using MATLAB(c) software, and the study area was then subset from the images to geographic coordinates of 36°9'-37°18'N, 7°48'-6º00'W. Rrs555 (sr^{-1}) 1km ocean data were used to calculate normalized water-leaving nLw555 (mW/cm^2 µm sr), derived as nLw555= F_0xRrs555, where F_0 is the annual spectral mean extraterrestrial solar irradiance, also called the solar constant. For the Aqua 545-565 nm band, the F_0 value corresponds to 186.09 mW/cm^2 µm (10). This nLw555 product is commonly utilized to discriminate and contour freshwater plumes, and is correlated better with the concentration of suspended sediments in near-surface waters than other wavelengths; hence it is a good proxy for the water discharged from river outflow after rainstorms (11, 12, 13). For each scene, the plume extension was delimited on the basis of the area covered by waters with high nLw555 backscattering rate. The indicator threshold to distinguish between "plume boundary" and the surrounding waters masses for the pixels has previously been defined by several authors as 1.3 mW/cm^2 µm sr (11, 12, 14, 15, 16). A Region Of Interest (ROI) offshore from the mouth of the estuary was defined, and Chl and nLw were calculated within the rectangle 36º36'-37ºN and 6º20'-6º40'W (see black rectangle in Figure 1). Therefore, for the quantitative estimation of the plume area, an evaluation of the sum of turbid pixels was performed, since each pixel is approximately 1 km^2. The final products corresponded to the instantaneous images (Chl and nLw555), which were further averaged into monthly composited, for analyzing the temporal and spatial variability of the Guadalquivir plume and chlorophyll patterns. These Ocean Colour products used to identify the complex variability of the estuary environment were validated against in-situ ground truth measurements of several coastal campaigns (17). The results obtained in that work demonstrate the precision of MODIS estimates in providing adequate resolution and sensitivity for accurate observation of Chl and Total Suspended Sediments (TSS) in the vicinity of the studied area.

RESULTS

Temporal variability of chlorophyll and turbidity in the Guadalquivir estuary

Figure 2 presents the time-series for the eight years of the period studied (2003-2010) of the daily precipitation (Rain, mm), daily river discharge from the Alcala del Río dam (Q, m^3/s), and the chlorophyll (Chl, mg/m^3), nLw 555 nm (mW/cm^2 µm sr) and Plume size (number of pixels with nLw 555 nm values greater than 1.3 mW/cm^2 µm sr) averaged in the ROI area. Common features and distribution of nLw are observed across the 8 years of images related to the seasonal pattern over the zone. The temporal variability of the turbidity of the estuary is marked by a consistent annual signal, with clear maximum values of nLw and plume size occurring in winter and early spring (rainy seasons) throughout all the years. The highest mean nLw values for the region are observed in January 2010 and December 2010 (4.3 and 4.6 mW/cm^2 µm sr, respectively). Most of the maxima nLw values across the Guadalquivir estuary occur near the coasts, presumably due to terrestrial discharge, and are associated with large extensions offshore. Moreover, lower and minimum values of monthly nLw means and number of pixels and extent related to the plume area are found in the summer and early fall seasons. The minimum record of nLw occurs in September 2007, with a mean of 0.6 mW/cm^2 µm sr. From the comparisons of nLw and plume size time-series it can be deduced that plume area presents a trend and behavior similar to nLw values, with maximum and minimum sizes of the plume in the ROI area showing good correspondence with the highest and lowest nLw levels, respectively.

Time-series of daily outflow from the Alcala del Río dam and daily precipitation measured at the Sanlucar la Mayor meteorological station are presented to illustrate the roles of local meteorological forcing on the ROI. Large inter-annual variations in mean precipitation can be observed, with long periods of very low rainfall in the summer and fall of 2003 and 2006, and heavy rainfall during several periods of the year (e.g., fall 2003, winter 2004, winter 2006, spring 2008, winter 2010). Seasonal cyclical oscillation of the plume and the presence of maximum nLw values appear to be superimposed on the increase in the precipitation over the mouth, also due to a combination of this and a significant increase in the river discharge from the Alcala del Río dam, especially in winter of 2010. Plumes of the greatest extent are presented in winter 2004, 2006, 2008, 2009 and 2010, corresponding to the most severe episodic storms and runoff events of the year. The highest mean nLw values appear coincident with the pronounced discharge events that occurred during the period studied (in January and December 2010). Events with large surface plume coverage occur during all the years coincident with extreme runoff rates. Otherwise, dry seasons and negligible discharges from the dam are often associated with minimum plume areas and low nLw mean records (e.g., in summers of 2003, 2006 and 2009). Finally, with respect to the information from the meteorological station, it has proved possible to establish a significant relationship between records of discharge, precipitation and the presence of the turbidity plume and its geographic extension. The last year, 2010, was an exceptionally wet year. Large discharge events are observed in winter and base flow remained high for the entire year less in the summer season. In Figure 2 it can be seen how the pronounced storms in winter and the consequent increase in the outflow from the dam lead to the occurrence of the turbidity plume in the ROI area, indicating that sediment plumes dominate the nLw signal.

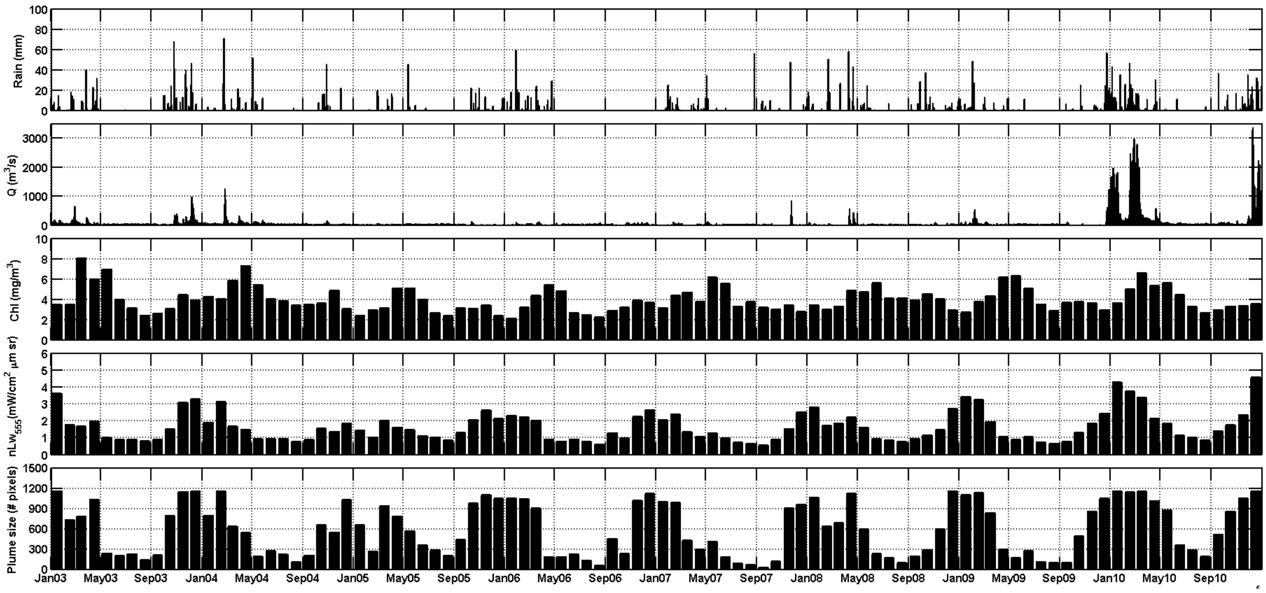

Figure 2. Regional mean time-series (2003-2010) of Rain, daily precipitation average measured at the meteorological station Sanlucar la Mayor (mm); Q, daily river outflow from the Alcala del Río dam (m^3/s); Chl (mg/m^3); nLw 555 nm (mW/cm^2 µm sr); and Plume size (number of pixels > 1.3 mW/cm^2 µm sr) averaged on a monthly basis from the MODIS data in the ROI area.

With respect to the regional mean Chl concentrations, they are characterized by clear interannual variations. Chl levels are highest especially during spring (maximum values recorded), showing considerable changes in the magnitude and duration of these peak events. The highest mean Chl record found in the ROI area is 8 mg/m^3 for the month of March 2003. Apart from these maximum Chl, another temporal pattern can be observed in which smaller blooms with less intense Chl values appear over the period studied, in late fall after the declining in summer. This semiannual signal with lower periodicity is visible in Figure 2. Therefore, Chl peaks seem to be the superposition of two distinct signals, accommodating asymmetric seasonal and annual cycles of chlorophyll by adjusting the timing and magnitude of maximum values. On the other hand, low Chl values remaining predominantly between 2 and 4 mg/m^3, are typical of late summer and early fall. The lowest Chl value observed (2 mg/m^3) is found during the month of January 2006. Monthly regional mean values of nLw and Chl present a clear relationship, with maximum Chl values recorded after the winter and early spring maximum nLw values, but with a time gap defined by the decreasing nLw of approximately three months as indicated in Figure 2. Hence, this temporal delay must be taken into account in considering the connection between the preceding storm events (and the concurrent rise of nLw values and development of the plume thereby induced) and high Chl values. The fact that the blooms occur with a temporal lag with respect to the peak of the plume development may be caused by the limiting effects of the flux of suspended sediments on rates of primary productivity and algal growth in the euphotic zone of the estuary (18). This time trend may also be due to the limited solar radiation existing during plume periods (winter and early spring); radiation then increases in the summer seasons when maximum Chl values are recorded.

Furthermore, the Chl pattern has suffered a decline from 2003 to 2006 and, from then on, an increase that is indicative of nutrient enrichment in the region during recent years. These phenomena are also associated with the increase in precipitation due to frequent storm events and the consequent intensification in river discharge, as was observed in the northeastern continental shelf of the Gulf of Cadiz (5,8). These events coincide with negative North Atlantic Oscillation (NAO) phases, and there is connection between the large-scale climatic pattern that dominates the index variation and the flood phenomena. Rainfall in the coastal sector of the Gulf of Cadiz is mostly dependent on and affected by the NAO; a clear and significant relationship ($r= -0.46$, $p<0.0001$) has been found between the annual cumulative precipitation and this index (8). The NAO is a climatic phenomenon that contributes greatly to variability in the weather system over the North Atlantic. The winter (December through March) index of the NAO is based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland since 1864. NAO index data was provided by the Climate Analysis Section (NCAR) [Boulder, USA], (http://www.cgd.ucar.edu/cas/jhurrell/indices.html) (19). As is described in the results, the pronounced episodes of rainfall intensify the river discharges and facilitate increased input of nutrients and suspended particulate matter to the continental shelf; consequently, the NAO has an important influence on productivity of the basin. We performed a comparison between the eight years (2003-2010) of the NAO index and Chl, nLw and Plume size annual averages (from December to March) of the total number of pixels in the ROI area. Correlation results of the NAO index against the remotely-sensed variables were: r= -0.26, p=0.53 for chlorophyll; r= -0.71, p<0.05 for nLw555 and r= -0.70, p<0.05 for the Plume size. According to these statistics of significant relationship with nLw and Plume size, we can reliably assume that, during the study period, both variables are robustly linked to the climatic forcing by the NAO index that occurs in the region, and thus represent a cyclic pattern of the variability on the shelf. Both river discharge and rain records are considerably higher for last year, 2010, compared with the previous years, which may have contributed to the increase in the nLw and Plume size values. The results demonstrate that the study area is subject to inter-annual patterns associated to climatic oscillations that control turbidity and chlorophyll distributions and therefore, the fertilization of the Gulf of Cadiz.

CONCLUSIONS

This work has demonstrated the potential of optical remote sensing for providing significant information and systematic quantification of the plume dynamics and its temporal and spatial variability on a consistent basis over an 8-year period and in a relatively complex system such as the Guadalquivir estuary (Case-II waters). Using validated satellite observations and supporting environmental data sets, we have developed robust satellite-derived indicators improving the representation of the behavior of turbidity and chlorophyll across the region. The results reveal the close connection existing between increasing precipitation, and the consequently large river discharges (negative NAO), and the development of the sediment plume in the estuary. Moreover, seasonal and inter-annual variability have been analyzed; results demonstrate that the main periodicities associated with turbidity and chlorophyll are the annual seasonal signals, with their maximum levels being reached in winter and early spring (rainy seasons), and in spring and early summer, respectively. Furthermore, chlorophyll distribution also presents a semi-annual pattern (linked to less intense peaks) appearing in late fall after declining in summer, throughout the control period. Consequently, terrestrial runoff events are the major processes regulating the fertilization of the basin, and increasing the input of enriched waters from the river to the continental shelf adjacent to the estuary. Such phenomena have contradictory effects because turbidity is the main limiting factor in the inhibition of primary production and phytoplankton biomass due to the obstruction of radiation in the water column, and to water quality degradation, with potentially negative impacts on humans and ecosystems. Hence, the use of MODIS data will present challenges to researchers in a variety of applications, particularly in coastal studies, to provide unique and critical information for scientists, decision-makers and environmental managers. We have addressed a range of issues that advance the transition of research towards operational application for monitoring the turbidity behavior of estuarine waters.

Future investigations will be focused on analyzing the spatial and temporal patterns of the turbidity plume on small-scales, and on incorporating meteorological and oceanographic factors such as wind, tide and currents to check the controlling mechanisms and improve our ability to assess and predict the complexity of plumes, especially in dry seasons. DEIMOS satellite images of high spatial resolution (24 m) will be used for characterizing small structures in this environment. Subsequent research work will also include the development of the Multivariate Empirical Orthogonal Function (MEOF) method for defining the connection between chlorophyll and turbidity.

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