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Assessment of temporal shifts of chlorophyll levels in the Egyptian Mediterranean shelf and satellite detection of the Nile bloom

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Abstract

Construction of the High Dam along the Nile at Aswan (Egypt) in the mid 1960s and subsequent anthropogenic influences have caused fall and rise of the Nile phytoplankton bloom and subsequent shifts in the pattern of chlorophyll distribution and phytoplankton levels in the Nile Delta shelf and SE Levantine. Despite previous research efforts, knowledge on mode of change or shifts of the Nile bloom and variability of chlorophyll concentrations in the Nile Delta shelf are still very limited and poorly documented. In an attempt to fill part of this gap, temporal and spatial shifts of the Nile phytoplankton bloom have been evaluated for the pre- and post-Dam years in this study using historically published research and field observations. The recent variability and long-term (1997-2006) trend of the Nile bloom has also been evaluated using merged satellite ocean colour data; the MedOC4 regional algorithm applied to a 10-year monthly satellite dataset from the ESA GlobColour project. The study area has been subdivided into two biogeographical areas; the coastal or inner shelf waters and outer shelf. This has been followed by application of the MedOC4 regional algorithm to remote sensing data of each area independently. The results of this analysis showed that the pattern of the Nile phytoplankton bloom has changed from a periodic pattern in the autumn, to a bloom that dominates most of the Nile Delta shelf during the winter and another bloom (reduced in extent and magnitude) during the other seasons. Results also show that there is an upward trend in the mean surface chlorophyll of the coastal water during the 10-year satellite period. This most likely ascribed to continuous addition of anthropogenic effluents and surface run-off from river mouths and other land-based sources. In contrast to inner shelf, the outer shelf and offshore water bloom events are occurring more regularly; recurrent in the winter and less pronouncedly in the spring. The mean surface chlorophyll concentration in the offshore area didn't show any significant change during the 10-year satellite period. Results reveal also the urgent need to adopt long-term monitoring programs for water sampling and in-situ measurements of bio-optical characteristics of the coastal and shelf waters off the Nile Delta and nearby Egyptian coasts. This is very important and critical for better understanding of marine biogeochemistry of the study area and validation of the present MedOC4 algorithm or adoption of a new bio-optical correction algorithm specific to Nile Delta shelf.

Keywords: Nile bloom, High-Dam effects, anthropogenic nutrients, chlorophyll variability, inner and outer shelf, ocean-color remote sensing.

1. Introduction

The Nile has historically been supplying Egypt and the whole SE Mediterranean, particularly at the time of the annual flood, with fresh water, fertile sediments and rich nutrients that were being derived through heavy rainfall and subsequent erosion of the volcanic Ethiopian high plateau during annual flood season (August-October). Through this regime the Nile built not only the highly fertile Nile Delta in the north of Egypt and the Nile Valley in the south, but also a highly fertile coastal water mass off the terrestrial Delta. This water mass was fertilised by the seasonal inflow of the nutrient-rich flood water (Halim, 1960) and contained a large and dense phytoplankton bloom hugging the terrestrial Delta coast at the time of the seasonal flood (Halim *et al*., 1967). The bloom also had a positive influence on the Egyptian Mediterranean marine fisheries (Halim, 1976; Bishara, 1984; Dowidar, 1984). Productive fisheries, especially sardines and prawns, were attracted to the Nile Delta and nearby coasts during the flood season because of the enrichment by organic matter.

However, since construction of the High Dam at Aswan in the mid 1960s, the traditional Nile regime and its historical bloom have been subjected to significant changes. Blockage of nutrient-rich sediments and river water flow by the damming effect has disrupted the bio-geochemical cycle and consequently suppressed the fertilizing effect of the annual flood. As a result, the Nile historical bloom disappeared from the Egyptian coast during the years immediately after completion of the High Dam (Aleem, 1972; Halim, 1976; Sharaf El Din, 1977; Halim *et al.*, 1995; Nixon, 2003; Halim, 2004). The disappearance of the bloom impacted negatively on the marine fisheries, with the total Egyptian Mediterranean coastal fish catch decreased dramatically to less than 25% of its pre-Dam total yield during the same period (Halim, 1976; Halim *et al*., 1995; El-Sayed & van Dijken, 1995). The biological productivity and fisheries ecosystem of the Nile Delta shelf persisted in such a state of imbalance before recovering again from the beginning of the early 1980s possibly due to improvement of nutrient supply and return of the Nile bloom.

Previous studies (e.g. Dowidar, 1984; Halim *et al*., 1976; Halim *et al*., 1995; El-Sayed & van Dijken, 1995; Nixon, 2003; Halim, 2004) indicated that the post-Dam phytoplankton bloom (after 1965) is different from the pre-Dam one in many aspects and that there were several shifts in the chlorophyll (chl-a) concentrations and phytoplankton levels in the Nile Delta shelf during the post-Dam years. According to these studies the pre-Dam (historical) bloom has changed from a seasonal 'diatomic' bloom into more diversified post-Dam (modern) bloom.

The post-Dam shifts of the Nile bloom were ascribed to effects of damming of the river Nile, channelisation of the Nile Delta and increases in the human population and development along the Delta coast. Erection of the High Dam at Aswan (in mid 1960s) and the subsequent channelisation of the Nile Delta has blocked most of the river loads of sediments, fresh water and natural fertilizers (Stanley, 1996) leading, therefore, to disruption of the biogeochemical cycle at the receiving basin (Halim *et al*., 1995; El-Sayed & van Dijken, 1995). On the other hand, the progressive increase of the anthropogenic effluents (due to population growth and development since early 1980s) delivered to Nile delta coast is believed to have enhanced nutrient supply in this area and hence led to an increase in chl-a levels (Figure 1) and the reappearance of the Nile bloom (Nixon, 2003; Halim, 2004).

2. Aims of the study

The present study aims to fill part of this gap through assessment variability of the Nile phytoplankton bloom using available in situ observations for the pre- and post-Dam periods and time-series analysis of long-term (1997-2006) merged satellite data (satellite-derived chl-a) from GlobColor ESA project on the Nile delta shelf and application of the regional MedOC4 bio-optical algorithm. The basic premise of this approach is that whilst available previous field observations and in situ chl-a measurements partially reveal the geographic distribution and some other characteristics of the Nile phytoplankton bloom in the past, particularly during the pre-Dam and immediate post-Dam years, satellite retrieval of chl-a can provide important information on recent trends and changes of the modern bloom.

The aims of this work can be summarised as:

(1) reviewing the mechanism and spatial distribution of the historical Nile bloom from published sources;

(2) assessing the current spatial and temporal pattern of the modern bloom through satellite retrieval of chl-a from available ocean colour sensors.

The major aim, beyond this, is to enhance our understanding of the role of anthropogenic activities in changing the biological regime and biogeochemical cycles in the estuarine and other coastal environments of Egypt's Delta.

3. Study area

The study covers includes the terrestrial Nile Delta and its continental shelf. The Delta encompasses about 12,000 km^2 of subaerial Delta plain and a comparable area offshore. The continental shelf off the Nile Delta is part of the Levantine basin and hence its hydrodynamic regime is controlled by the overall regime of the Levant and SE Mediterranean. Unlike the other parts of the Levant, the continental shelf off the Nile Delta is very wide and reaches the 200 m depth contour at about 60 km offshore. It consists of a series of terraces separated by low slopes that are bisected by drowned channels and a major submarine canyon fronting Rosetta promontory (Summerhayes *et al*., 1978). According to Misdorp and Sestini (1976), the Nile Delta shelf can be classified into three provinces; the inner shelf (0-36 m depth); middle shelf (36-75 m depth); and the outer shelf (>75 m depth). However, Sestini (1989) classified it into only two provinces; the inner continental shelf (to 50 m depth) and the middle to outer continental shelf (50-100 m depth).

The Levantine basin is known to be extremely nutrient-depleted and therefore ultra-oligotrophic (Yacobi *et al*., 1995). Factors contribute to this include the general circulation of the Mediterranean Sea with a west to east surface current bringing relatively nutrient-depleted water from the North Atlantic, the arid climate of the region and scarcity of rivers which can act as point sources for nutrients. Surface chl-a values in the Levantine basin normally don't exceed 0.4 mg/m^3 (Dowidar, 1984; Abdel Moati, 1990; Krom *et al*., 1991; Yacobi *et al*., 1995) except near the Nile Delta coast and other adjacent coasts where it can be as high as 80 mg/m^3 (EIMP-CWMP, 2007); in particular within coastal areas that lie in front of the Nile mouths, lakes outlets, harbours and urban falls.

The Deltaic plain hosts four coastal brackish water lakes, in addition to one relatively open lagoon at its extreme eastern side (Figure 1). From the west to east these are: Mariut, Idku, Burullus, Manzala and Bardawil. With the exception of Mariut, all the other lakes are connected to the sea through outlets or narrow openings dissecting the sandy barriers and maintaining open exchange with the sea. The southern and eastern limits of these lakes are receiving increasing amounts of agricultural runoff and sewage effluent through agricultural drains and urban outfalls (Nixon, 2003). Unlike the adjacent Levantine waters, the Delta lakes are eutrophic and highly productive; they periodically experience eutrophication problems. Lake Manzala is the most productive with productivity reaching more than 1 g C/m^2/hr (Hamza, 1985; Abdel-Moati & El-Sammak, 1997).

At least two thirds of Egypt's habitable land is located in the Nile Delta, which hosts also about 60% of the national industry, 80% of agricultural land and most of the trade and fishing activities of the country (Moufaddal, 2005). Also most of Egypt's population and large cities are located in the Delta whereby their effluents and sewage wastes are discharged directly into the coastal waters or indirectly to the agricultural drains and coastal lakes (Figure 1). Lake Mariut, for example, receives all of the Alexandria City sewage (9-10 x 10^5 m^3/day), in addition to approximately 3 x 10^8 m^3/day of agricultural drainage (Abdallah, 2003; El-Rayis, 2005). Manzala also receives a substantial amount of sewage from Cairo (~ 3 x 10^9 m^3/day) as well as 7 x 10^9 m^3/day of agricultural drainage (El-Sherif & Gharib, 2001). The other two lakes, Edku and Burullus are least affected, receive 2 x 10^9 and 3 x 10^9 m^3/day of agricultural drainage, respectively (Samman, 1974; Khalil, 1998).

Aquaculture is very active in the northern Delta, particularly around the coastal lakes, and fish farms are now considered one of the most widespread land-use activities in the northern Delta (Moufaddal, 2007). Effluent and drainage water discharged from these fish farms represent an additional source of nutrient input to the Delta lakes and coastal waters.

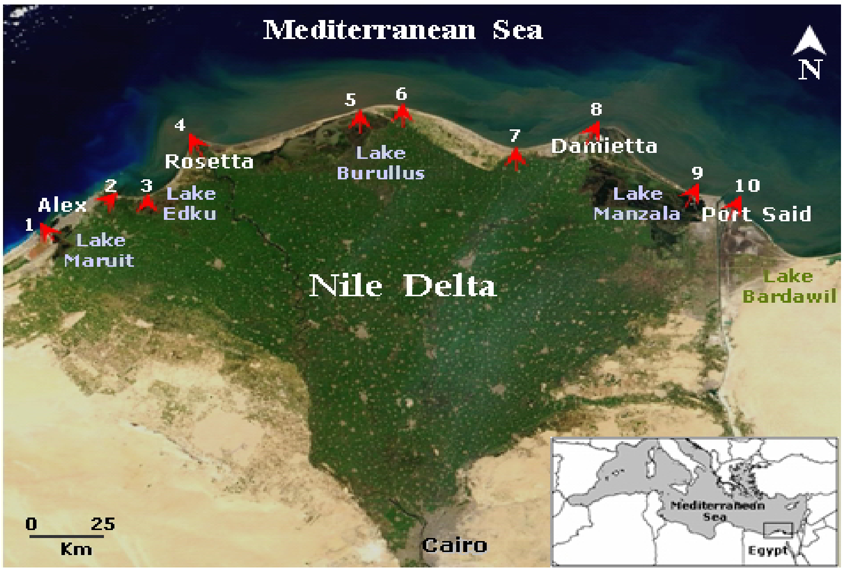

Figure 1: The Nile Delta and its main features (coastal lakes and Nile bloom) highlighted on a MODIS image taken on 5 February 2003. Arrows and numbers indicate locations of major urban outfalls, drains, lakes outlets and river branches and other surface-run off sources on the Nile delta coast. Image courtesy of the MODIS Rapid Response Team at NASA/GSFC.

4. Data and methods

4.1. Previous research work and available field observations

A review of the historical Nile bloom and description of its spatial and temporal coverage was based on information derived from available local studies on the Nile delta shelf that include Halim (1960), Halim *et al*. (1967), Aleem and Dowidar (1967), Wahby and Bishara (1980), Dowidar (1984) and Nixon (2003). Other relevant studies such as Halim (1976, 1991, 2004), Halim *et al*. (1995), Aleem (1972), El-Sayed and van Dijken (1995) and Nixon (2003) were also of use although they can be considered as syntheses of the earlier studies.

In addition to these studies, there have been only three regular monitoring research programs during the post-Dam period from 1965 to present. The first was carried out by Dowidar (1984) through funding from USAID, which focused on the quantities and distribution of chl-a and primary productivity along the Nile Delta shelf between El-Agami in the west and El-Arish in the east during 1982. Other parameters measured included salinity, dissolved oxygen and nutrient content in the coastal and oceanic waters; from surface waters to 300 m depth.

The second monitoring program was carried out in 1994 and also funded by USAID and aimed to study the dynamics of food relationships along the southeastern Mediterranean coastal shelf ecosystem with the goal of outlining the food webs linked to commercially important species (El-Sayed & van Dijken, 1995). The project included only one marine cruise with a regional coverage, undertaken in autumn 1994, and several local cruises off the Nile Delta coast. The regional cruises sampled the continental shelf off the Nile Delta from Marsa-Matruh in the west to Al-Bardawil in the east; surface water down to 200 m with Chl-a, SO_4, NO_2/NO_3, NH_4, and total N and total P measured.

The third monitoring program was initiated in 1998 with funding from the Danish International Development Agency (DANIDA) as renewable 5-years program to establish an integrated environmental monitoring program for the ambient air and national seas of Egypt. An important component of this program was the Coastal Water Monitoring Program (EIMP–CWMP) that aimed to monitor pollutants and other water quality parameters in the Egyptian coastal waters, biota and sediment in both the Mediterranean and Red Seas. Monitoring of the Mediterranean coastal waters was carried out six times a year from a total of 45 stations spanning the Egyptian coast from El-Sallum in the west to Al-Arish in the east. Measurements at each station include physical, biochemical (Chl-a, NO_2/NO_3, Total N, Total P, PO_4 and SO_4) and bacteriological parameters. The spatial and temporal coverage of this program undoubtedly makes it the longest and largest scale monitoring program to be carried out to date.

4.2. Satellite ocean colour data and the MedOC4 bio-optical algorithm

The main data set used for this study is a 10-year time series (September 1997 to December 2006) of GlobColour monthly averaged data created from the merging of SeaWiFS, MODIS-Aqua and MERIS. GlobColour is an ESA Data User Element (DUE) Project (*http://www.globcolour.info*) that developed a satellite based ocean colour data service to support global carbon-cycle research and operational oceanography (Pinnock *et al*., 2007). In the present work, surface chl-a was computed by applying the MedOC4 regional bio-optical algorithm (Volpe *et al*., 2007) to the GlobColour fully normalised reflectance products (ρ).

Earlier Mediterranean studies (e.g. Bricaud *et al*., 2002; Claustre *et al*., 2002; D'Ortenzio *et al*., 2002) have demonstrated that the standard global NASA algorithms (OC2v4 and OC4v4) lead to a significant overestimation and uncertainty in the satellite derived chl-a concentration within coastal areas (Bosc *et al*., 2002; Bricaud *et al*., 2002; Volpe *et al*., 2007) whose optical water properties and water-leaving radiances are affected by the presence of coloured dissolved organic matter (CDOM) and/or suspended particulate matter (SPM) input from river channels and land-based sources (Bontempi & Yoder, 2004; Lavender *et al*., 2004; Lavender *et al*., 2005). Regional algorithms can provide a solution as they can perform better where there is local in situ data to train them. A number of regional bio-optical algorithms, mostly derived from the NASA global algorithms (OC2 and OC4), have been proposed for chl-a retrieval in the Mediterranean including Gitelson *et al*. (1996) for application to the Coastal Zone Color Scanner (CZCS) and Bricaud *et al*. (2002), D'Ortenzio *et al*. (2002) and Volpe *et al*. (2007) for use with SeaWiFS.

Among others, the MedOC4 algorithm has been shown to be most suited (Volpe *et al*., 2007) for the Mediterranean waters; in terms of unbiased satellite chl-a estimates and improving satellite uncertainty in coastal Mediterranean waters. Volpe *et al*. (2007) successfully used it for retrieval of satellite surface chlorophyll concentrations in the Mediterranean. The results confirmed that the MedOC4 performs much better than other existing regional algorithms.

Unfortunately, contemporaneous in-situ chlorophyll and optical measurements for the neritic and inshore waters of the Nile delta shelf are very local, sparse and without continuity in time. In view of scarcity and unavailability of this kind of data, it was not possible for the present study to build a new bio-optical correction algorithm for the delta shelf or to validate results of performed remote sensing analysis. Hence, application of the MedOC4 algorithm which is proved to be best and most available correction algorithm for the Mediterranean water environments, has been taken as a good compromise and the best available solution for assessment variability of chl-a in the delta shelf and satellite detection of the Nile bloom. Validation and confidence in the computed chl-a data was only supported by the green colouration of the water (Figure 1.) which can be taken as good indication for higher concentrations of chl-a or phytoplankton, despite it is also accepted that high CDOM and SPM concentrations can exert an adverse affect on chl-a algorithm.

The MedOC4 is an empirical 4th order polynomial expression (Eqn. 1) based on the OC4 functional form (O'Reilly *et al*., 1998, 2000), but the coefficients are locally determined for the Mediterranean Sea.

$$Chl_{MedOC4} = 10^{(0.4424 - 3.686R + 1.076R^2 + 1.684R^3 - 1.437R^4)} \quad (1)$$

Where:

R = $\log_{10}$ (max (ρ_{443}, ρ_{490}, ρ_{510})/ ρ_{555}),

ρ = Remote sensing reflectance at 443, 490 and 555 nm

4.3. Geographical coverage

In order to detect the surface chl-a variability and its spatial changes across the Delta shelf, the area was divided geographically into two bio-geographical areas (Figure 2) and the GlobColour satellite dataset was analysed separately for each area. The divisions were made subjectively based on knowledge of the biophysical regimes (effects alongshore currents and surface run-off on quality and productivity of coastal water off the delta coast) prevailing in each area, separation of the continental shelf water from open ocean water and latitudinal limits of the historical Nile bloom in regard to the modern one.

The first division covers a large part of the continental shelf off the Nile Delta, from the limits of the coastline to ~ latitude 31.8 N which includes the coastal waters from the Delta coastline to a depth of roughly 50 m (Figure 2). This area receives effluents and fresh water from two riverine estuarine inputs (two branches of the Nile) and another eight land-based sources (lakes outlets, sewage pumping stations and urban outfalls; see Figure 1). It's also known to be influenced by the east-trending longshore current of the east Mediterranean (Halim, *et al*. 1995; Halim, 2004; Moufaddal, 2005).

The second division is smaller rectangular area and covers the middle and outer shelf, as well as part of the open ocean waters off the Delta from latitude 31.8 N to 32.2 N (Figure 2). The southern limit of this area is believed to be an active area for frontal eddies and coastal filaments that occasionally export highly productive coastal waters into the oceanic areas through horizontal advection (Groom *et al*., 2005). Being part of the SE Mediterranean, the area is also characterized by the presence of deep chlorophyll maxima at a depth of about 75 to 150 m (Dowidar, 1984). This layer might be upwelled through vertical mixing to enrich the surface oceanic waters with nutrients and higher chl-a concentrations (Dowidar, 1984; Adel-Moati, 1990; Krom *et al*., 1991; Yacobi *et al*., 1995).

5. Results

The following two sections are synthesis of previous field observations from available studies and aim to show the main biogeochemical aspects and spatial characteristics of the Nile phytoplankton bloom before and after construction of the High Dam. However, the third following section is based exclusively on time-series analysis of ocean color remote sensing data and aims to assess recent variability and trend of surface chl-a and phytoplankton concentration across the Delta shelf and the two biogeographical divisions of the study area.

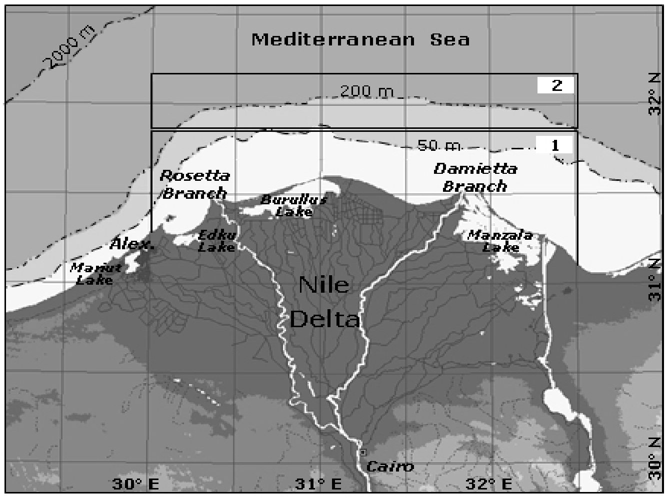

Figure 2: The geographical location of the two studied biogeographical areas within the Nile Delta shelf.

5.1. The pre-Dam conditions: The historical Nile bloom

Prior to construction of the Aswan High Dam, most of the annual Nile fresh water and sediments were discharged along with their dissolved and adsorbed nutrients to the receiving basin off the Nile Delta coast (Halim *et al*., 1976; Stanley, 1996); between 134 and 56 x 10^6 t of sediment (Shukri, 1950) and 84 to 34 x 10^9 m^3 of water each year (Halim, 1960). Most of this discharge was from the two mouths (Rosetta and Damietta) of the Nile River during the flood season (August-October) with average flow rates of 6 x 10^3 m^3/s or even more (Vörösmarty *et al*., 1999; Nixon, 2003). The outflow then progressed rapidly eastward along the coast of Egypt as a turbid coastal current, the Nile stream, and then northward along Asia Minor (Halim, 1976; Saharf El Din, 1977; Halim *et al*., 1995; Halim, 2004).

The Nile outflow had sharp boundaries with a sudden discontinuity in salinity, density, turbidity and nutrients (Halim, 1960). The seaward width of the outflow, its eastward and northward extension in the Levant basin and the total area covered depended upon the height and duration of the flood wave. According to Halim *et al*. (1967), in 1964 the outflow showed exceptional horizontal spreading over the continental shelf off the Egyptian coast. Its boundary front, along the isopycnal of 26, was detectable about 90 km north from Rosetta. It then narrowed eastward to a strip about 25 km in width over depths of 100 m. According to these observations, the effect of the Nile outflow could be detected as far eastward as the Lebanese coast (Halim, 1960; Emery & George, 1963; Halim *et al*., 1967). The outflow also spread considerable amounts of nutrients along the neritic and oceanic waters off the Delta coats and this impacted positively on marine productivity and the whole food chain of the area (Halim *et al*., 1995).

During an average flood, the total discharge of nutrients was estimated to be 5.5 x 10^3 t of phosphate and 280 x10^3 t of silicate per year (Halim, 1976; El-Sayed & van Dijken, 1995). Estimates of Halim (1991, 2004) and Halim *et al*. (1967, 1995) showed that the 1964 flood season, which is considered to be the last high flood before closing of the High Dam, released about 8.2 x 10^3 t of dissolved phosphate and 410 x 10^3 t silicate into the Nile Delta shelf. The amount of the adsorbed fraction of phosphate is believed to be at least five times higher than the dissolved fraction (Halim *et al*., 1995). According to Nixon (2003), the annual Nile flood was delivering from 7 to 11 x 10^3 t of phosphorous, 7 x 10^3 t of nitrogen and 110 x 10^3 t of silica. In any case, inflow of these nutrients with the annual flood water was enough to trigger an exceptionally large and dense phytoplankton bloom off the Nile Delta shelf. This Nile bloom was initiated within a few hours of the flood discharge and was extensive in both space and time (Halim, 1991). However, it was confined to the upper surface water layer of 5 to 10 m depth. The greenish colour of the Nile bloom mixed with the reddish brown colour of the suspended sediments giving rise to the characteristic brownish green colour along the continental shelf waters off the Nile Delta.

The phytoplankton assemblage of the seasonal bloom was exclusively composed of diatoms (Halim, 1960; Aleem & Dowidar, 1967). The bloom magnitude was variable from year to year and from one location to another along the Nile Delta coast, where it was much larger and massive in Rosetta estuary than Damietta with a variation of standing crop in the order of one million individual cells up to ten millions or more per litre (Halim, 1967; Aleem, 1972). Controlling factors included volume of the incoming fresh water and laden sediments, prevailing hydrodynamics and concentration of natural fertilizers in the flood water. The Nile bloom also supported a productive marine fishery; especially sardines and prawns off the Nile Delta. Between 1962 and 1965 an average of 37 x 10^3 t of sardines were caught per year (Wadie, 1982; Nixon, 2003). Estimates of Aleem (1972) show that the marine fisheries landed from the Egyptian Mediterranean coasts in 1964 account for 23% of the total fish catch of Egypt.

5.2. The post-Dam conditions: The modern Nile bloom

Damming of the river Nile at Aswan in 1965 resulted in a control of the river drainage and cut-off most of the adsorbed and dissolved nutrients that were input to the Delta shelf with the Nile flood each autumn. The volume of Nile water outflowing to the Egyptian coast dropped from about 53 x 10^9 m^3 in 1964 to only 18 x 10^9 m^3 and 12 x 10^9 m^3 in 1965 and 1966 respectively (Halim, 1976). This amount has further dropped to its present day level of 2.5 to 4 x 10^9 m^3 (Halim *et al*., 1995).

Blockage of this material has suppressed the fertilization of the shelf waters and led to a disappearance of the historical Nile bloom. Previous reports of Aleem (1972), Halim *et al*. (1976) and Dowidar (1984) showed that the phytoplankton standing crop in the Nile delta shelf rarely exceeded a few thousands cells per litre during the post-Dam flood, comparing to ~ ten millions of cells per litre during any pre-Dam flood. In addition, the composition and relative abundance of phytoplankton populations has been altered significantly. Diatoms are no longer the dominant component of the coastal waters with the dinoflagellates becoming equally important (Halim *et al*., 1976; Dowidar, 1984; Halim, 2004). In situ measurements presented by Dowidar (1984) on the seasonal distribution of chl-a and primary productivity in 1982 revealed that the seasonal cycle of chlorophyll biomass was unimodal with a conspicuous peak in the winter and another less pronounced one in the spring.

According to Dowidar (1984), ranges of the seasonal chl-a concentration varied between 0.6-6.0 mg/m^3 in winter, 0.2-2.5 mg/m^3 in spring, 0.02-0.5 mg/m^3 in summer and 0.06-0.6 mg/m^3 in autumn. According to the same study, the potential rate of organic production in autumn is much higher than any another season with the primary productivity showing a relatively higher rate during the summer. Consequently, Dowidar (1984) postulated that the late summer and early fall period may still be functioning as the 'biological spring' in the SE Mediterranean despite the standing crop of phytoplankton being low. This paradox referred to the heavy grazing of planktivorous fish that may limit production by maintaining the phytoplankton standing crop at relatively low concentrations.

Reduction of the natural fertilizers and the subsequent suppression of the Nile bloom also led to a collapse of fisheries. The decline in the catch of sardines was especially dramatic, from an annual average of almost 37 x 10^3 t between 1962 and 1965 to 6.5 x 10^3 t from 1966 through to 1970 (Wadie, 1982). El Sayed and van Dijken (1995) also showed that the sardine fishery total catch decreased from 18 x 10^3 t in 1962 to about only 550 t in 1968 and 1969. Fisheries bottom trawl surveys off the western part of the Nile Delta showed an almost 80% decline in average fish and shrimp abundance between 1960–1961 and 1969–1970 (Wadie 1982).

The decline in marine fisheries off the Nile Delta persisted for about 15 years when it began to recover again from the beginning of 1980. By the late 1980s, total fish catch from the Egyptian Mediterranean coast exceeded the levels prior to the closing of the High

Dam (Halim *et al*., 1995; El Sayed & van Dijken, 1995; Nixon, 2003; Halim, 2004).

Recovery of the marine fisheries could suggest enhanced rates of primary production (Nixon, 2003) and a return of the Nile phytoplankton bloom. However, it might also possible that increasing of fishing grounds and fishing techniques effort after resolution of the military conflict and signing a peace treaty with Israel in 1979 contributed to this. According to Halim (2004) both decline and recovery of fisheries yields during the period 1967-1980 can not be taken as outcome of a single event. Taking this into consideration, the recovery can be interpreted as the result of a combination of factors; the restoration of normal conditions of fishing activities accompanied improvement of fishing techniques (Halim, 2004) and progressive increase of agricultural effluents and other nutrient-rich anthropogenic run-off (Nixon, 2003; Halim 2004).

5.3. Recent trends of the Nile bloom: An ocean colour remote sensing approach

Unfortunately, with the exception of the study of Dowidar (1984), data from those monitoring programs and studies which devoted to study productivity or biogeochemical aspects of the Nile Delta shelf water, hasn’t been made publicly available and therefore cannot be used to document the status of the Nile bloom during the period from the early eighties until 1997; the start date for the satellite dataset used in this study. Also coverage of the Nile Delta shelf and the SE Mediterranean, in general, by CZCS (the first ocean colour satellite that operated from 1978 to 1986) was very poor and therefore, very few images were taken for this region; they are not enough to form a time series or draw conclusions about the chl-a seasonal patterns during the lifespan of CZCS (1978-1986).

In the present study, the monthly surface chl-a distributions were calculated for the two selected areas (Figure 2) and the results are presented in Figures 3 to 5. The seasonal pattern, temporal and spatial changes of the chl-a distribution in the two areas are shown in Figures 3 and 4. Winter imagery show the highest phytoplankton chl-a concentrations, in both coastal and offshore waters, whereas in summer and autumn there is an apparent decay of the Nile bloom despite the occurrence of local hot spots close to shore. A south to north gradient in surface chl-a concentrations for the whole region can also generally be observed.

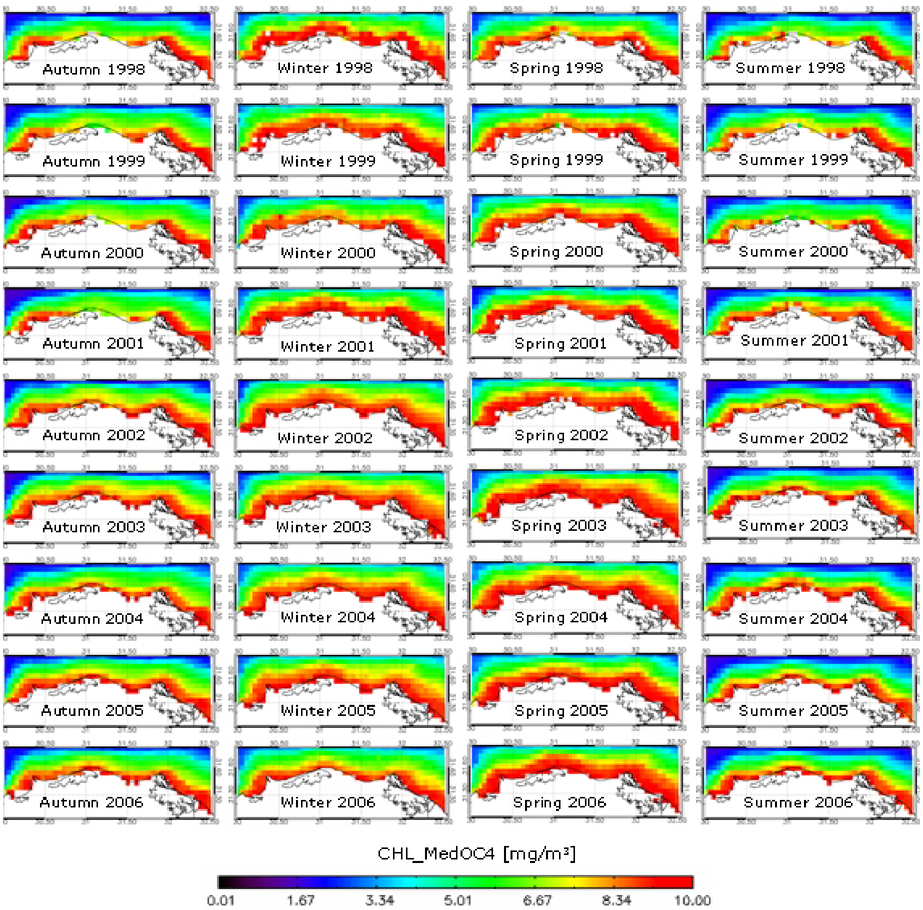

Figure 3: Seasonal mean chl-a maps for the inshore and coastal waters off the Nile Delta (biogeographical area 1 in Figure 2) as calculated using MedOC4 algorithm.

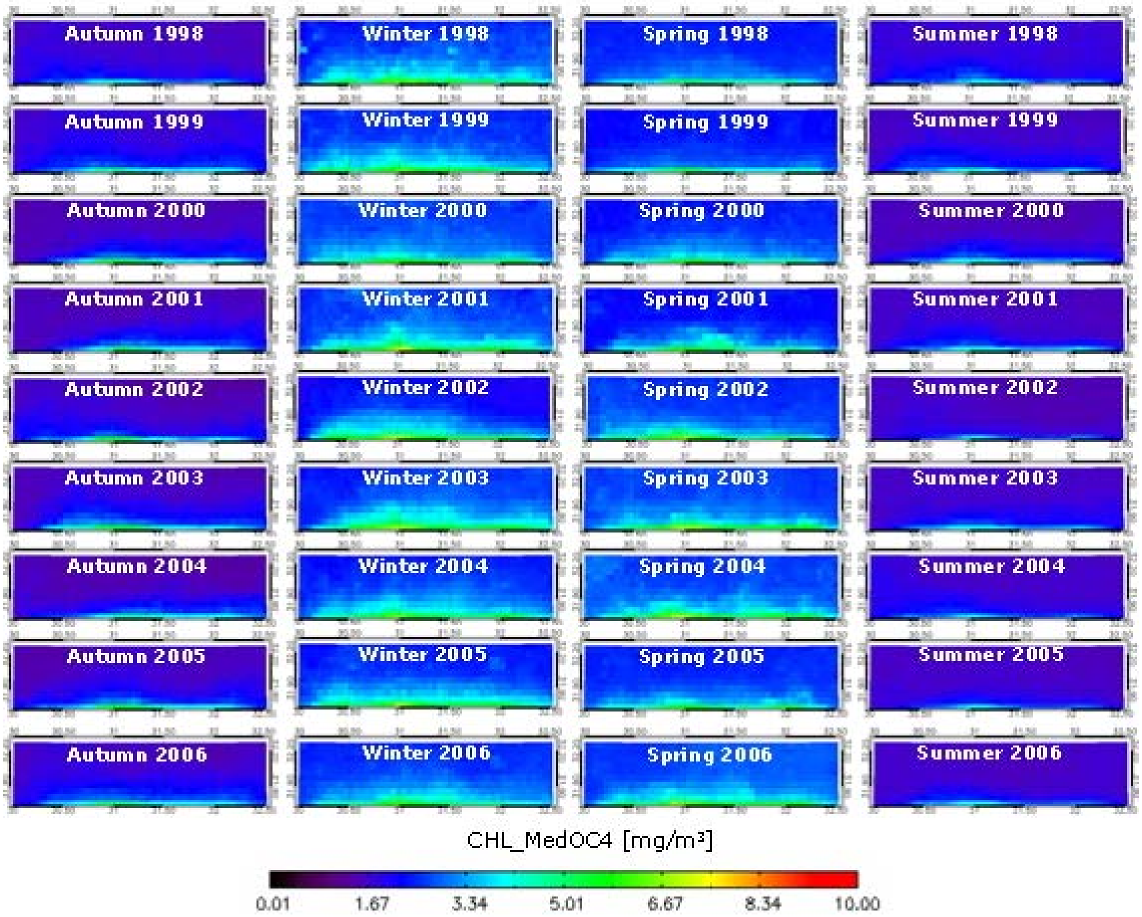

Figure 4: Seasonal mean chl-a maps for the offshore waters off the Nile Delta (biogeographical area 2 in Figure 2) as calculated using MedOC4 algorithm.

In Figure 3, it is evident that the phytoplankton bloom off the coastal area (area 1 in Figure 2) is present most of the year, although it becomes more confined to the coast (reduced in geographical extent) in the summer and autumn. The bloom is also stronger and more pronounced near the outlets of the Egyptian coastal lakes and urban outfalls. In the offshore area (area 2 in Figure 2), the bloom is more evident in the winter and spring; being oligotrophic in the other seasons (Figure 4). Overall, this pattern indicates that the Nile bloom has been shifted temporally and spatially as compared to the pre-Dam conditions.

Figure 5 demonstrates the mean monthly surface chl-a variations within the two selected areas; a trend line has been calculated and overlaid. The coastal region has a larger range of chl-a concentrations (~ 1 to 3.25 mg/m^3) compared to the outer shelf and open sea areas (0.03 to 0.15 mg/m^3). Seasonal patterns are evident in both transect areas and agree with the results of Dowidar (1984) that was based on field sampling and in situ measurements.

From Figure 5 it is clear that the highest mean chl-a concentrations for both areas are found primarily during the winter. Mean surface chl-a begins to increase (in both areas) in November reaching its highest concentration (3.25 mg/m^3) in January; March and April also have relatively high concentrations. Subsequently chl-a begins to decrease during May, reaching its lowest concentration from June to August. This pattern clearly shows the disappearance of the autumn Nile bloom and its replacement by a winter bloom. In addition, the mean chl-a concentration in the coastal area and inner shelf appears to have an upward trend, from the data available, while it appears steady (no significant change) in the outer shelf waters.

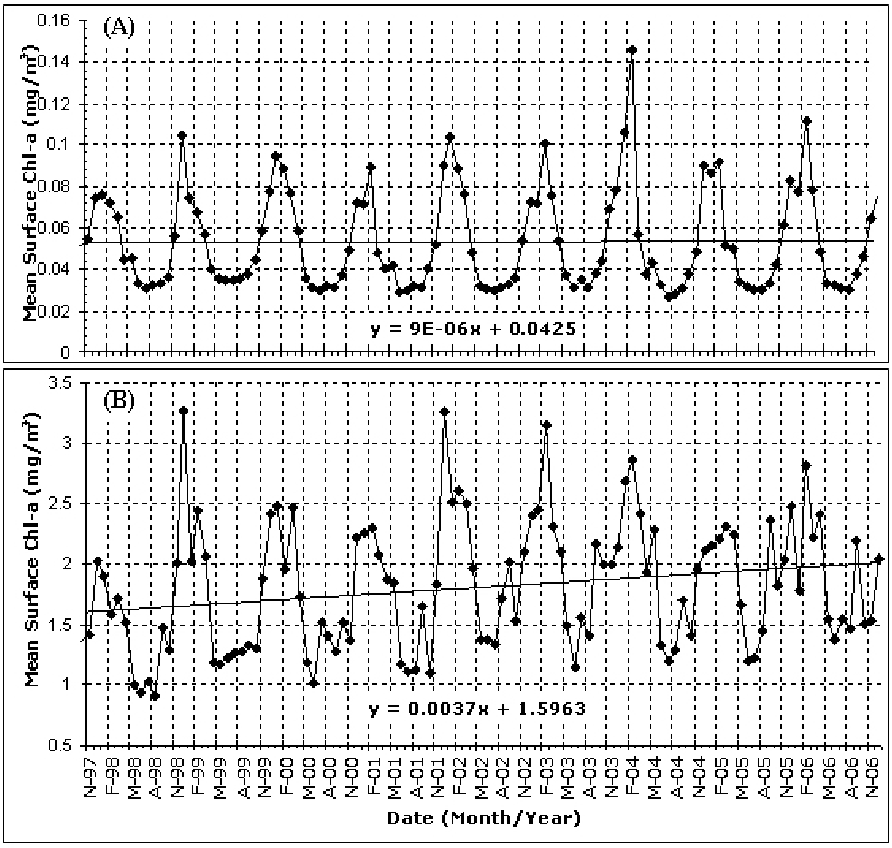

Figure 5: Mean monthly chl-a variations in (A) the outer shelf and (B) the coastal waters off the Nile Delta calculated using GlobColour reflectance time-series and MedOC4 regional algorithm of Volpe *et al.* (2007). Overlaid on the plots is a trend line, with the equation given at the bottom of each plot.

6. Discussion

Construction of the High Dam in the mid 1960s resulted in a blockage of most of the sediment and water into the reservoir (Lake Nasser) behind the Dam. Channelisation of the Delta, by an intensive network of drains and canals, has also contributed to this effect through further entrapment of the riverine sediment load, water and natural fertilizers in the Delta (Stanley, 1996). With the loss of about 90% (Halim *et al*., 1995; Nixon, 2003; Halim, 2004), or even more, of the floodwater the coastal waters off the Nile Delta and Levantine basin are no longer fertilized or replenished with dissolved and silt-adsorbed nutrients. This has led to a disappearance of the historical autumn Nile bloom from the mid 1960s to probably the late 1970s (Aleem, 1972; Halim, 1976; Dowidar, 1984).

Unfortunately, a lack of in situ measurements and field studies during this period make it very difficult to determine the exact timing or duration of this shift. Information on the spatial distribution and biological characteristics of the Nile bloom during the period from approximately the mid 1980s to mid 1995s was also restricted by a lack of satellite ocean colour and in situ data. The only available research work was undertaken by Dowidar (1984), which revealed a recovery of the Nile bloom and change of the chl-a seasonal cycle off the Delta coast into a single winter bloom.

An analysis of ocean colour satellite imagery (GlobColour dataset with the MedOC4 algorithm applied) between 1997 and 2006 confirmed the return of the Nile bloom and its predominance along the whole Nile Delta shelf in winter and spring with an upward trend for the mean surface chl-a concentrations in the coastal waters off the Nile Delta and no significant trend for the outer shelf. The seasonal pattern seen in the outer shelf area agreed with the mean monthly SeaWiFS chl-a variations (1997 to 2004) presented by Groom *et al.* (2005) who used the regional algorithm of Bricaud *et al*. (2002).

A recovery and shift of the Nile bloom can be explained by the increase in anthropogenic nutrient supply due to increased human population and associated anthropogenic activities, which has replaced the effect of the annual Nile flood. According to Nixon (2003), there has been a dramatic increase in the human population and a subsequent dramatic extension of the urban water supplies and sewage collection systems in Lower Egypt and the northern parts of the Nile Delta since the early 1980s. Human population in the large cities such as Alexandria and Cairo and other urban areas of the Nile Delta has doubled or tripled in about three decades (1970-2000), where the population in Alexandria has increased from 1.5 million to ~ 3 million and in Cairo from 6 million to ~ 18 million. Amounts of human wastes reaching the Mediterranean from both cities also were increased from ~ 25 000 tonnes in 1965 to about 100 000 tonnes in 1995 Nixon (2003). By the late 1990s, over 3 x 10^6 m^3 per day of sanitary sewage industrial waste water were discharged from Alexandria city directly to the coastal waters off the western coasts of the Delta (Halim and Shouk, 2000). Also, use of artificial fertilizers to Delta farmlands has increased about linearly since that date, climbing to more than one million ton annually beginning from the mid-1990s Nixon (2003) to ultimately find their way to the Delta shelf with the intricate network of irrigation canals and agricultural drains of the Delta.

Variability of surface chl-a and its distribution pattern, in the two bio-geographical areas off the Delta (Figure 2) can be assumed to be controlled by two different regimes; the physical oceanographic processes that dominate the outer shelf and the anthropogenic effluent associated with the surface run-off from river mouths and land-based sources that influence the inner shelf and coastal waters. In the outer shelf and deep water areas, wind stress and severe weather conditions during the winter can play an important role in enriching the surface water with higher chl-a concentrations. During intensely cold winter weather, the convective mixing may penetrate the nutricline and hence deeper nutrient-rich waters leading to an upwelling of these nutrients (Bontempi & Yoder, 2004). This could explain why the outer shelf off the Delta has higher chl-a concentrations in winter (Figure 5). Studies of Dowidar (1984) and El-Sayed and van Dijken (1995) also suggested convective mixing as a possible mechanism for the input of "new" nutrients to the surface waters. In reverse, the decline in chl-a concentrations in the outer shelf from May to October can be ascribed to an increase in stratification and decrease in vertical mixing.

Continuous surface run-off from the two branches of the Nile, and the other land-based sources (urban outfalls, lakes outlets, pumping station), supply the coastal waters with organic and inorganic nutrients so are the likely explanation for the persistence of the bloom spreading across the coastal and inshore areas of the Delta (see Figure 1) most of the year time. Only minimal amounts of the waste waters (agricultural drainage, raw sewage and industrial effluents) are subjected to primary treatment (Halim and Shouk, 2000). Therefore, they represent a prime and continuous source of nutrients to the coastal waters. Other anthropogenic sources include aquaculture activities and fish farms, which use high quantities of artificial fertilizers and are widespread along the Delta coast. Predominance of the Nile bloom along the whole Egyptian shelf in winter, and its shrinkage during the other seasons, can be attributed to maximum discharges occurring during the winter when there is increased precipitation and hence also irrigation water (Youssef Halim, *pers commun*.).

The upward trend of the mean chl-a in the coastal waters could therefore be attributed to the effects of continuous and ever-increasing addition of organic and inorganic nutrients from surface-runoff and anthropogenic sources along the Delta coast. As mentioned above, development and human population in Egypt and particularly along the Nile Delta coast have increased substantially beginning from early 1980s Nixon (2003) and are likely to be responsible for increase of nutrient input to the coastal waters off the Delta. Sewage infrastructure and areas being exploited for aquaculture activities and fish farms have also increased substantially since that date. For example, areas of fish farms around lake Burullus have increased from 330 to 346 km^2 in only five years from 2002 to 2007 (Moufaddal, 2007). Progressive addition of anthropogenic nutrients from aquaculture activities and other anthropogenic sources has to be impacted positively on phytoplankton growth off the Delta coast particularly in winter and spring and are likely responsible for the enrichment of the coastal and shelf waters with higher chl-a concentrations.

7. Conclusions

The Nile bloom has subjected to regime shifts more than once during its modern history; at least three phases can be distinguished since the early1960s. The first phase characterized the pre-Dam period when the phytoplankton growth off the Nile Delta coasts was in state of equilibrium and enriched continuously by the annual Nile flood; the Nile bloom occurred periodically each autumn and was linked to this seasonal flood. The second phase initiated in mid 1960s, after closure of the Aswan High Dam, and continued until the early 1980s. During this time the Nile bloom and shelf waters experienced a dramatic drop in phytoplankton chl-a concentrations and collapse of the coastal fisheries. The third phase, which started in early 1980s and continues until the present (2006 for the data analysed in this research), could be described as a return of the Nile bloom and change from a periodical natural pattern to more massive and continuous (artificial) one with more pronounced peaks in mean surface chl-a concentrations in the winter and spring instead of the autumn. A common feature of the latter pattern is predominance of high chl-a concentrations near the Nile Delta coasts and in areas opposite to lakes outlets and urban outfalls.

Analysis of the ocean colour satellite data also showed an upward trend for the mean surface chl-a concentrations in the coastal waters off the Nile Delta while there was no significant trend for the outer shelf. Whilst the convective mixing and other physical oceanographic processes are likely to be responsible for surface chl-a blooming in the outer shelf, continuous addition of anthropogenic effluent and surface run-off from river mouths and other land-based sources are most likely responsible for a progressive enrichment of the coastal waters.

The present study shows that ocean colour remote sensing can provide important information on surface chl-variability and phytoplankton blooms in highly dynamic areas such as the Nile Delta shelf. Confidence in the chl-a data presented is supported by the green colouration of the water (Figure 1.), but it's accepted that high CDOM and SPM concentrations can adversely affect chl-a algorithms and so in situ chl-a measurements (to backup the trends seen in the satellite data) would have been preferred. The MedOC4 bio-optical algorithm, despite being validated in the Mediterranean, still needs validation within the Nile bloom region and strengthens the urgent need for a regular monitoring programme within the Egyptian Mediterranean shelf and more specifically in front of the Nile Delta. In line with the aspirations of the Group for Earth Observation (GEO) this in situ data should be made publicly available.

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تقييم التغيرات الزمنية لمستويات الكلورفيل في المياه الأقليمية المصرية للبحر المتوسط، والرصد الفضائي لمد النيل الطحلبي

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من الثابت أن إنشاء السد العالي على مجري نهر النيل عند أسوان، وبقية الأنشطة البشرية اللاحقة لهذا الحدث قد تسببت في وجود تغييرات كبيرة في نمط توزيع وتركيزات الهائمات النباتية الدقيقة (الفيتوبلانكتون) وكذلك في نسب تركيز محتوى الكلورفيل في المياه الإقليمية المصرية أمام دلتا النيل وجنوب شرق بحر الشام، ما بين صعود وهبوط. وعلى الرغم من الجهود البحثية السابقة، إلا أن المعلومات والبيانات المتاحة عن أنماط هذا التغيير وتوقيتات حدوثه، لازلت محدودة للغاية، وغير موثقة بشكل كاف.

لذا ومن منطلق الرغبة في محاولة سد هذه الفجوة العلمية، فقد أجريت خلال الدراسة الحالية محاولة لتقييم ورصد التغيرات الزمنية والمكانية الحادثة في نسب وأنماط توزيع تركيزات الفيتوبلانكتون والكلورفيل الكائنة بمنطقة الرف القاري البحري لدلتا النيل، في الفترات الزمنية السابقة والتالية مباشرة لإنشاء سد أسوان العالي، وهذا من واقع بعض البيانات والقياسات الحقلية المتاحة والتي تم جمعها سابقا على هذه المنطقة. كما جرى تقييم نمط التغييرات الحديثة خلال فترة عشرة سنوات (1997-2006) واتجاهاتها خلال هذا المدى، من خلال الاستعانة ببيانات الاستشعار عن بعد المدمجة (ESA GlobColour project merged data) والخاصة بمستشعرات رصد ألوان المياه السطحية، وهذا من خلال تطبيق أحد النماذج الخوارزمية الإصحاحية الخاصة بمنطقة البحر الأبيض المتوسط، والمعروف باسم MedOC4 regional algorithm. هذا وقد جرى تقسيم منطقة الدراسة إلى قسمين، الأول يضم نطاق المياه الساحلية والرف البحري الداخلي لدلتا النيل Inner Shelf، والثاني يضم نطاق المياه العميقة ومنطقة الرق البحري الخارجي Outer Shelf، حيث تم تطبيق الخوارزم المذكور وبقية تحاليل الاستشعار عن بعد عليهما، كل على حدة.

وقد بينت نتائج هذه التحاليل أن موجات مد النيل الطحلبي Nile phytoplankton bloom قد تغيرت بالفعل توقيتات ظهورها ومساحة امتدادها في منطقة المياه الساحلية أمام دلتا النيل، من مجرد موجة ازدهار طحلبي كلاسيكية وقصيرة نسبيا، إذ كانت عادة ما تظهر خلال فترة الخريف فقط، وهذا فيما قبل مرحلة بناء السد العالي، إلى موجة ازدهار طحلبي حديثة، أكثر امتدادا وتظهر بداية من فصل الشتاء وقد تمتد حتى الربيع. كما بينت النتائج أنه خلال فترة العشرة سنوات من 1997 وحتى 2006، كانت هناك زيادة عامة واتجاه عام تصاعدي بالنسبة لتغير متوسط تركيزات الكلورفيل خلال منطقة الدراسة. وقد أعزى هذا إلى الزيادة المضطردة في كميات مياه الصرف الآدمي والزراعي الغنية بالمغذيات والعناصر العضوية القادمة عبر فرعي النيل والمصارف ومخارج الصرف الواقعة على امتداد ساحل الدلتا. وفي مقابل هذا، فقد أوضحت النتائج أن نمط ظهور وتوقيتات موجات الازدهار الطحلبي النيلي تبدو أكثر انتظاما وأكثر نمطية في منطقة المياه البحرية العميقة التالية للمنطقة الساحلية لدلتا النيل، إذ تظهر أو تزيد فقط خلال موسم الشتاء فقط، ودون ملاحظة وجود أي اتجاه تصاعدي أو تغيير مؤثر في تركيزاتها خلال فترة العشر سنوات المشار إليها.

وفي الخلاصة توصي نتائج ومستخلصات الدراسة بضرورة وجود برنامج رصد حقلي منتظم وطويل المدى لرصد خصائص المياه الإقليمية المصرية (الساحلية والبحرية العميقة) أمام دلتا النيل من حيث

مواصفاتها البيولوجية والطبيعية، ومعاملات جودة المياه فيها، حيث تمثل هذه النوعية من البيانات أهمية خاصة بالنسبة لقدرتنا على فهم التغيرات الجيوكيمائية والبيولوجية الحادثة في المياه المصرية الإقليمية أمام دلتا النيل. كما تعد هذه البيانات حجر الزاوية بالنسبة لعملية تأكيد صلاحية الخوارزم الإصحاحي المعروف باسم MedOC4 للتطبيق على تلك المياه، وكذلك بالنسبة لإمكانية تقديم نموذج أو خوارزم جديد خاص بهذه المنطقة، يمكن من خلاله قياس تركيزات الكلورفيل والفيتوبلانكتون من صور الأقمار الصناعية بشكل منهجي وبدقة كبيرة.