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Research Article

COASTAL EUTROPHICATION: EFFECT OF NUTRIENT RUNOFF

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ABSTRACT

The near-shore coast of the Mississippi discharge region was selected to show the dynamics of eutrophication by using satellite derived data. Sea surface temperature, chlorophyll, normalized fluorescence line height and the absorption coefficient were analyzed with linear and polynomial fits to reveal the oscillatory nature of changes in the near-coastal region. The steepest increase in chlorophyll is during the summer period and, in looking beyond, the predicted values for the same season in 2035 would be around 5.5 mg m^{-3}, that corresponds to an increase of about 175%. The steady increase of chlorophyll in the effluent of the Mississippi has to be viewed against the increasing export of nutrients by the river because 89% of total nitrogen inputs into the Mississippi River are derived from agricultural runoff and drainage

Keywords: *Eutrophication, Mississippi, Prediction, Remote Sensing*

INTRODUCTION

As the growing world population required an increase in food production, agricultural resources with new technologies were introduced during the industrial revolution in the 1700s. It was especially the introduction of synthesized fertilizers, based on the Haber-Bosch process that changed the agricultural practices. However, that change resulted also in emission of harmful waste from production and consumption. Furthermore, with the start of the 'Green Revolution' in the 1940s, it took less than half a century to recognize that the use of synthesized nitrogen fertilizers also altered the global nitrogen cycle by doubling the flow of reactive nitrogen. Human activity also increased the global flux of nitrogen and phosphorus from land to the oceans twofold and threefold, respectively (Howarth et al., 2002; Howarth and Marino, 2006). There is a strong indication that this trend will continue. Already in 2009, it was estimated that the world will need 60% more cereal production between 2000 and 2050 (FAO, 2009) and accordingly, the need for fertilizers would surge. In response, production, consumption and undesirable byproducts will further rise. Anthropogenic emission of nitrogen by the mid-1990s contributed new nitrogen to the environment at a rate of 140 Tg nitrogen y^{-1}. That is equivalent to the natural rate of global biological nitrogen fixation on all the land surfaces (Vitousek *et al.*, 1997; Cleveland *et al.*, 1999). The rate at which humans have increased the supply of reactive, biologically available nitrogen far exceeds the rate at which humans have increased CO_2 in the atmosphere that is responsible for global warming (Vitousek *et al.*, 1997).

Management of fertilizers and mitigation of its side effects have a high global priority in order to further engineer an acceptable nutrient flow to the environment. The international community recognized that global crop production and the world's food security are dependent on nutrients, especially nitrogen and phosphorus compounds. However, it was noted that global economy-wide nitrogen-use is extremely inefficient because over 80% of anthropogenic reactive nitrogen is lost to the environment. This loss leads to water, soil and air pollution that threatens human health and wellbeing as well as ecosystem services (UNEP 2019). Not all fertilizers used in agriculture are converted to biomass as a high percentage of fertilizers is lost to washoff and enters the marine coastal environment. Although low in concentration, emitted nutrients enhance the natural primary productivity and pose a problem in mitigating the effect that is known as eutrophication. The causes of eutrophication can occur naturally but can also be the result of emitted nutrients from agricultural fertilizer runoff and sewage discharge. Basically, eutrophication is the effect of added nutrients to the ecosystem that can be natural or is a result of anthropogenic sources. As an outcome of eutrophication, there are now worldwide, more than 400 coastal hypoxic systems covering an area that > 245,000 km^2, and about half the global riverine nitrogen input of 50 to 80 Tg year^{-1} is anthropogenic in origin. Furthermore, anthropogenic nitrogen deposition is concentrated in coastal waters downstream of industrial and agricultural regions (Doney, 2010).

In the United States, the mid-Atlantic coastal region is apparently the most affected by eutrophication as pointed out by Bricker et al., (2008). Increasing nutrient discharge through the Chesapeake Bay and the Albemarle-Pamlico Estuarine System is mainly a result of increasing population, land use change and nutrient load due to growing animal populations and an increase of N-based fertilizers (Kemp et al., 2005). Up to about 80% of NH_3 originate from swine operations in North Carolina (Aneja et al., 2003). About 10% to 40% of the total N input to estuaries comes from atmospheric deposition, including deposition directly onto the water surface and the watershed (Environmental Protection Agency, 1999).

Anthropogenic sources differ as they originate either as diffused or point source but govern the export of dissolved inorganic nitrogen and dissolved inorganic phosphorus at the global scale (Seitzinger et al., 2005). It is forecasted that by 2050 anthropogenic produced nitrogen in riverine fluxes will be around 75 Tg N yr $^{-1}$ most of which is delivered to coastal waters (Galloway *et al.*, 2004). It is anticipated that the dimension of global flux of nutrients to coastal ecosystems will increase further with consequences especially in developing countries.

Eutrophication in coastal regions also has a socio-economic impact due to oxygen depletion in the water column that triggers reduction in fish and shellfish stocks and the development of toxins from algal blooms. For example, it was estimated that about eight percent of the nitrogen applied in the US corn belt is being directly exported through the Mississippi into the Gulf of Mexico. Including the loss to the farm production, the cost to the Gulf marine economy is about US $1.4 billion annually (Good and Beatty, 2011).

In the early 1990s, anthropogenic nitrogen was about 156 Tg N y^{-1} showing an increase by a factor of about ten compared to the data for 1860 (Galloway et al., 2004). By1996, the use of nitrogen fertilizer was the equivalent of about 83 Tg N y^{-1}, and approximately half of the inorganic nitrogen fertilizer that was used globally was applied within 15 years (Howarth, 2002). However, the various fertilizer components show a different growth in demand, a greater demand for potassium than for phosphorus and nitrogen as a result of steady improvements in management practices and more effective fertilization (International Fertilizer Association, 2019). Although those changes reflect a slight improvement in the management of application and consumption, they are partly negated by an increase of population and the associated additional food requirements. Therefore, it can be anticipated that further utilization of fertilizers and resulting eutrophication will intensify as indicated in the global fertilizer demand and forecast that shows the need of about 203.5 Mt nutrients for 2023/2024. As not all applied fertilizer is incorporated into biomass, a large percentage is washed off from the field into groundwater, streams, rivers and finally into the coastal zone.

The level of eutrophication in coastal regions has been altered by certain changes in agricultural practices and environmental policies as shown for coastal regions of the Yangtze River estuary, the offshore region of Manila Bay, the New York Bight, the offshore area close to Chesapeake Bay and the Mississippi coastal region (Szekielda, 2020). While several regions showed reduction in chlorophyll levels, the Mississippi's near coastal water showed an increase in chlorophyll concentrations during the last decades. The environmental impact of nutrient loading in the

Mississippi River can be illustrated with the large areal extent of hypoxia in the northern Gulf of Mexico that is to a high degree related to substantial nitrogen loading from the Mississippi River basin. An estimate showed that about 89% of total nitrogen inputs into the Mississippi River is derived from agricultural runoff and drainage, and about 8% of the nitrogen is directly exported into the Gulf of Mexico via the Mississippi River (Good and Betty (2011). Nitrate load in the Mississippi increased noticeably over much of the last half-century, rising from 200,000-500,000 tons per year in the 1950s and 1960s to an average of about 1,000,000 tons per year during the 1980s and 1990s (USGS, 1915). It is in this context, that remote sensing data collected during the last decades over the Mississippi effluent will be analyzed to identify temporal changes that are in the timeframe of global changes.

MATERIALS AND METHODS

The area of observations has been placed close to the Mississippi effluent and covers the region 91^0W, 28^0N, 88^0W and 29^0N as shown in Figure 1A.

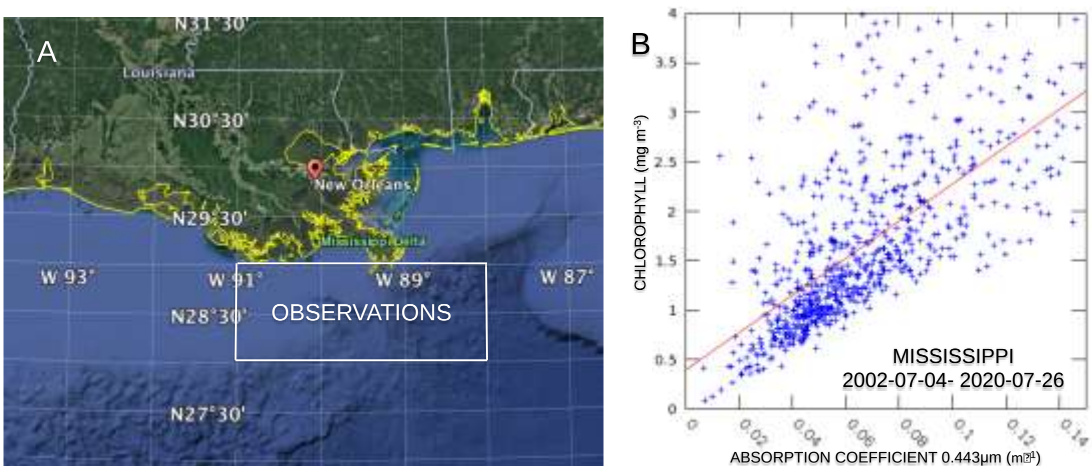

Figure 1: A. Location of observations in the Mississippi effluent at 91^0W, 28^0N, 88^0W and 29^0N. B. Comparison of chlorophyll concentration with the absorption coefficient at 0.443µm (m^{-1}). The correlation R= 0.666.

Remotely sensed data were accessed from the System for Multidisciplinary Research and Applications (NASA Giovanni). Giovanni is constructed for the analysis of Earth remote sensing data products on weather, climate, atmospheric composition and dynamics, oceanography and hydrological processes. The main parameters used in this study were derived from optical measurements. The Terra and Aqua satellites collected with the moderate resolution imaging spectroradiometer (MODIS), data in 36 spectral bands. This resulted in the production of parameters that were used in this study:

1. Chlorophyll concentration is expressed in units of mg m^{-3} and is a data product from the NASA Ocean Biogeochemical Model (NOBM).
2. Sea surface temperature was measured during daytime through the atmospheric window at 11µm and are expressed in centigrade. Remotely sensed temperature estimates the surface skin temperature of the sea surface that may differ slightly from the actual sea surface temperature.
3. The absorption coefficient (m^{-1}) due to phytoplankton is measured at 0.443 µm and binned to 8-daily composites at 4 km kilometer resolution.
4. Chlorophyll sun-induced fluorescence is measured at 0.678 µm and is expressed as normalized fluorescence line height in mW cm^{-2} μm^{-1} sr^{-1}.

The algorithm for remotely sensed chlorophyll estimates semi-quantitative concentration, but in coastal waters, the algorithm for chlorophyll concentration is influenced by other non-living material that is either present in particulate or dissolved form and cannot properly be discriminated from each other. This includes chromophobic dissolved organic matter and suspended inorganic and organic substances.

Figure 1B shows a comparison between chlorophyll concentration and the absorption coefficient at 0.443µm, where the spectral region of the α-absorption band of chlorophyll is located. The comparison gives a reasonable agreement especially at lower concentrations. Although the correlation R= 0.666 is not very high, it shows that the changes observed can still be qualitatively interpreted as ocean color fluctuations in time and space. Thus, in the following, the term chlorophyll will be used with the understanding that the data used in this study refer to ocean color rather than to a specific photosynthetic pigment. Nevertheless, it allows determining qualitatively the spatial and temporal extent of areas that are influenced by river effluent as has been demonstrated with application of SeaWiFS data showing river discharge and chlorophyll in coastal regions (Acker et al., 2009).

RESULTS

The near-shore hydrography of the investigated Mississippi region is dominated by the river discharge and like in other rivers eutrophication is an outcome of discharge volume and the concentration of delivered nutrients. The annual cycle for the Mississippi discharge as measured at Baton Rouge shows its maximum during Spring and reduced discharge is observed starting in July-August throughout the Fall season as shown in Figure 2 for 2019.

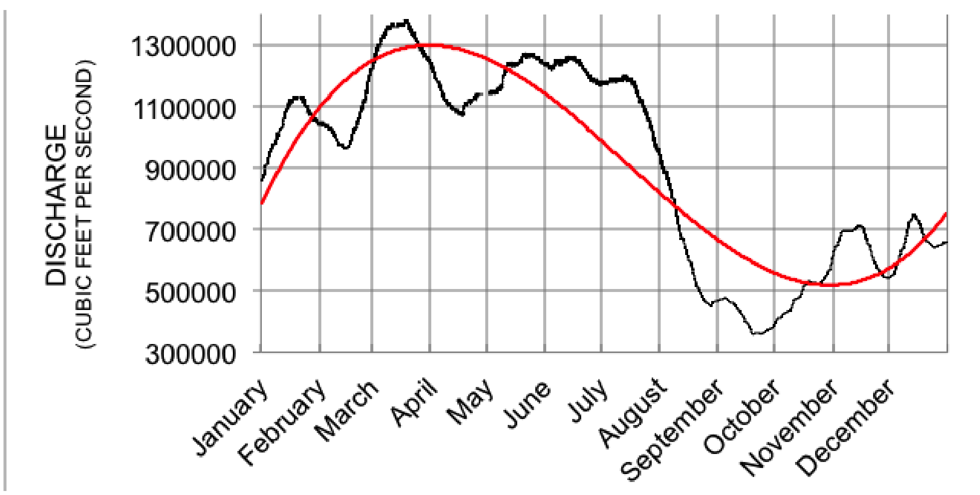

Figure 2: Annual discharge of the Mississippi in 2019 based on data from USGS 07374000, Mississippi River at Baton Rouge, LA.

Monthly averaged chlorophyll images for 2019 shown in Figure 3 reveal the patchiness of chlorophyll and concentration changes during the year in response to river discharge, although wind and turbulent mixing affect the surface distribution of chlorophyll as well.

The region undergoes seasonal temperature fluctuations between 18C and 32C with a well-pronounced interannual cycle as shown in Figure 4A. The year-to-year changes are resolved with the time series of temperature as shown in Figure 4A, with monthly area-averaged surface temperature, that shows that in 2010 an anomaly is also reflected in the chlorophyll data. The corresponding chlorophyll concentrations in Figure 4B reveal the annual cycle but high heterogeneity is recognized because changing precipitation and washoff from inland contribute to varying nutrient transport rate and concentration that determines the formation of plankton in the near-shore region.

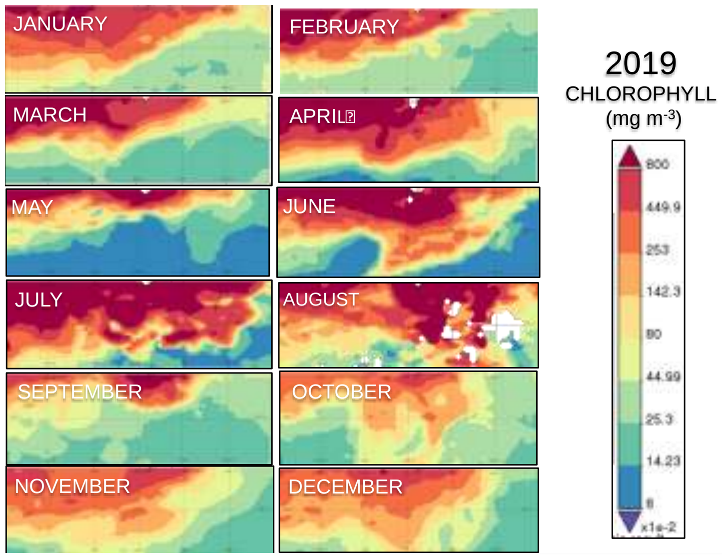

Figure 3: Mapping of chlorophyll concentration (mg m^{-3}) in a time series for 2019 at four km resolution.

Previous studies showed that the Mississippi River had a significant decrease in chlorophyll concentrations and this decrease was interpreted as an influence of high-discharge events and as a possible outcome from federal and state government efforts to reduce the anoxic and hypoxic benthic zone near the Mississippi River delta by decreasing nitrogen output to the river (Acker *et al.*, 2009). However, the minimum chlorophyll concentrations found in 2004 showed afterwards a steady concentration increase.

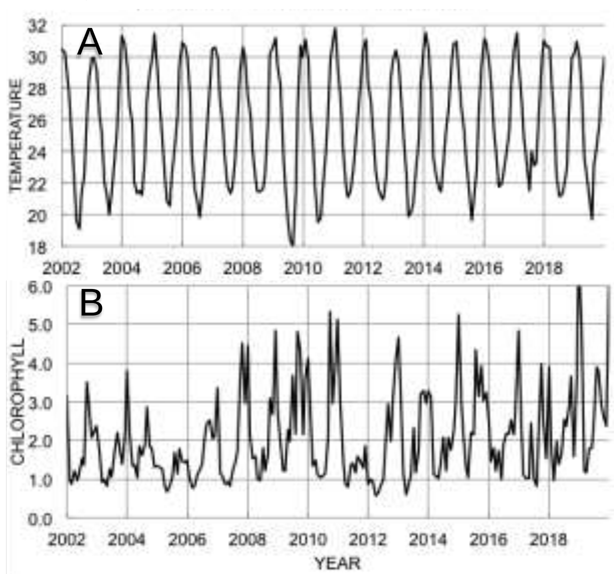

Figure 4: A. Time series of monthly area-averaged day sea surface temperature (^{0}C) at 11µm and 4 km resolution in the area of observation. B. Time series of area-averaged chlorophyll concentration (mg m^{-3}) at 4 km resolution.

The longitudinal averaged data are shown with the Hovmoller-presentation of temperature sea surface temperature is shown in Figure 5A and the corresponding display for chlorophyll is given in Figure 5B. The chlorophyll data show the highest levels close to the coastal region that undergoes large interannual variations, and the extended peak in 2010 relates to the temperature anomaly for the same year. Fluctuations of chlorophyll in the north-south direction is an outcome of the varying extension of the river discharge plume in response to seasonal changes, as is shown in the example for the 2019 discharge data.

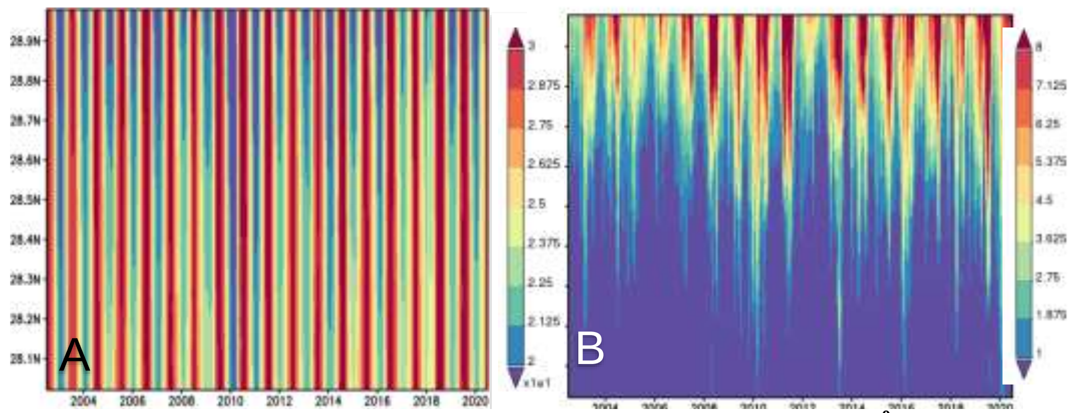

Figure 5: A. Hovmoller longitude-averaged sea surface temperature (^{0}C). B. Hovmoller longitude-averaged chlorophyll concentrations (mg m^{-3}).

In order to identify long-term changes, linear and polynomial 3rd fits were applied to sea surface temperature, chlorophyll concentration, fluorescence line height and the absorption coefficient at 0.443µm. It is evident in Figure 6 that all four parameters have an increasing trend. Temperature shows changes from about 25.4C to 25.8C while chlorophyll increased from about 1.5 mg m^{-3} to about 2.5 mg m^{-3}, and a similar trend is observed with fluorescence measurements and the absorption coefficient.

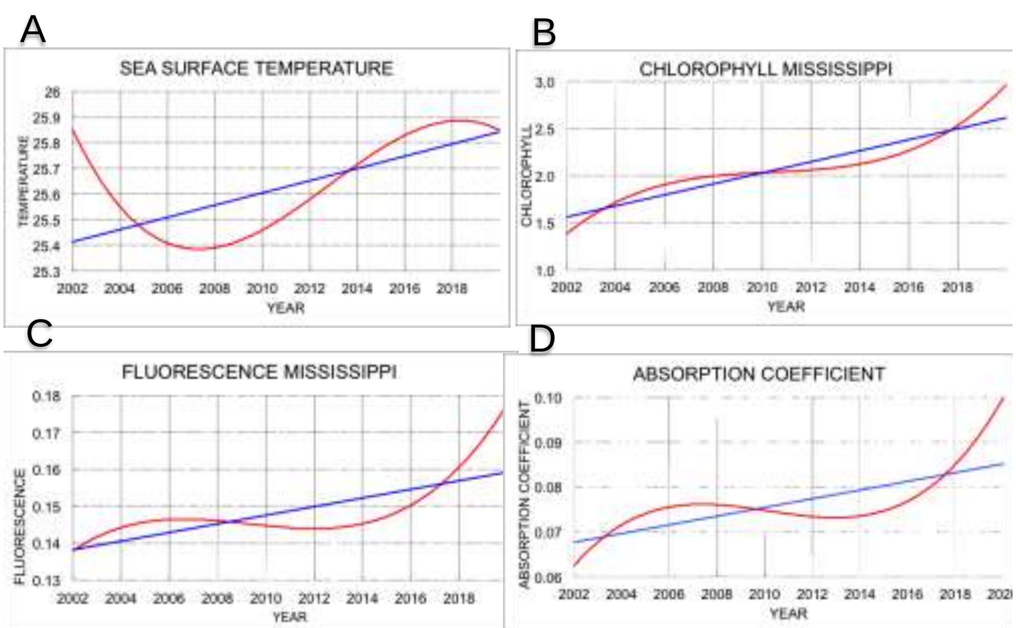

Figure 6: Linear and polynomial 3rd fit for A: Sea surface temperature (C). B: Chlorophyll (mg m^{-3}). C: Normalized fluorescence line height. All data are monthly averaged and have a 4 km resolution. D: Absorption coefficient due to phytoplankton at 0.443µm.

The polynomial fits also realize the oscillating nature of the changes. Keeping in mind however that this analysis incorporates yearly and interannual changes, the results are fused and seasonal fluctuations may not be appropriately resolved. Therefore, chlorophyll measurements were grouped by seasons as shown in Figure 7, and it is evident that the data reveal a continuous increase in concentration, but highest increase is observed for June through August. The linear regressions for chlorophyll during the four seasons are shown in Table 1 and were used to predict concentrations for 2035. This estimate is based on the assumption that the changes continue in a linear development.

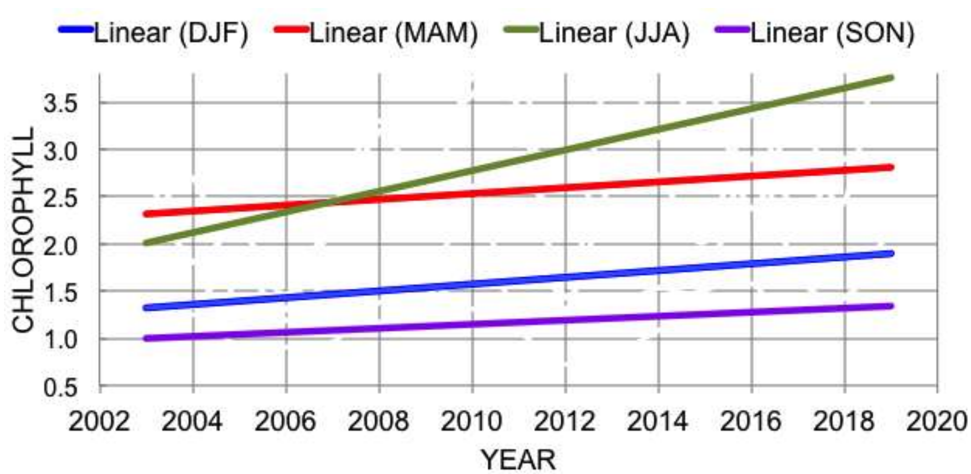

Figure 7: Interannual time series for chlorophyll (mg m^{-3}) based on linear regressions.

Table 1: Regressions for chlorophyll concentration and predicted change by 2035.

LINEAR REGRESSIONS OF CHLOROPHYLL CHANGES			
SEASON	**REGRESSION**	**2003**	**2035**
Dec to Feb	y = 0.036x - 70.831	1.3	2.4
Mar to May	y = 0.0309x - 59.576	2.3	3.3
Jun to Aug	y = 0.1094x - 217.09	2.0	5.5
Sep to Nov	y = 0.0214x - 41.854	1.0	1.7

DISCUSSION AND CONCLUSIONS

The polynomial fits in Figure 6 show the oscillatory nature of changes, and therefore a linear fit may not be the most appropriate tool for forecasting. However, the estimate for the next fifteen years, as shown in Table 1, indicates the range of changes that can be expected. Based on the regressions, the steepest increase in chlorophyll is during the summer, and the predicted values for the same season in 2035 would be around 5.5 mg m^{-3}, that corresponds to an increase of about 175%.

The steady increase of chlorophyll in the effluent of the Mississippi has to be viewed against the increasing export of nutrients by the river. During 2000–2014, the export of total nitrogen was twofold larger than that during the first decade of the twentieth century, and dissolved inorganic nitrogen export increased by 140%, dominated by nitrate and total organic nitrogen (Tian *et al.*, 2020). Historical data show that concentrations and loadings to the adjacent continental shelf accelerated since the 1950s to 1960s (Rabalais *et al.*, 2001; Rabalais *et al.*, 2002, Pellerin *et al.*, 2014). As has been pointed out, eutrophication in the Mississippi coastal region increased through the impact of deforestation, wetland conversion and expansion of agricultural drainage that removed part of the Mississippi basin's natural capacity to withhold nutrients from runoff draining into the Mississippi system (Rabalais *et al.*, 2002).

The data presented in this study indicate the probability of high chlorophyll concentrations in the Mississippi effluent in the future. As chlorophyll is highly related to primary production, more frequent or severe hypoxia and negative consequences of nutrient loadings to coastal waters can be expected. That confirms the need to reduce the nutrient flow in order to prevent further water quality degradation (Rabalais *et al.*, 2009). As removal of nutrients to a level that would prevent eutrophication is at present an engineering challenge, and reducing the agricultural discharge of fertilizers is a long way down the road. Implementation of new policies as well as monitoring by remote sensing the environmental changes could however assist in mitigating a further increase in eutrophication.

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