International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081
An Open Access, Online International Journal Available at http://www.cibtech.org/jgee.htm
2020 Vol. 10(2) May-August, pp.128-137/Szekielda

Research Article

EUTROPHICATION: THE ANTHROPOGENIC OFFSHORE SIGNAL

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ABSTRACT

Chlorophyll measurements by satellites have been used to build time series over decades with the objective to demonstrate that the level of eutrophication can be related to alteration in agricultural practices and environmental policies. Coastal sites were selected with varying degrees of anthropogenic inputs and agricultural activities. Included in this study are the Amazon River estuary, 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. Trends over seventeen years show the link to major environmental management changes that affected the nutrient flow and changes in eutrophication of the coastal areas. Reduction of nutrient load initiated by legislative measures is recognized in the offshore region through varying chlorophyll concentrations. However, in order to detect this effect large data sets with time series are required. Observations particularly in the Mississippi and Yangtze outflowing water indicate that the eutrophication offshore signal documents not only the effect of nutrient discharge but also the changes in land use practices.

Keywords: *Eutrophication, Coastal Oceanography, Nutrients, Land Use Practices*

INTRODUCTION

With increasing population pressure and rising discharge of anthropogenic products in the coastal areas, a threat emerges to the ecological functioning of the coast. The major nutrient loading to the ocean is from land surfaces and from anthropogenic material that is emitted from domestic and industrial sewage, animal waste, fertilizer, and atmospheric fallout. It is directly linked to the population size and its level of development. In this regard, eutrophication through nutrient emission has accelerated global change (Howarth and Marino, 2006; Smith, 2003, 2006, Doney, 2010). In response to excessive nutrient loading, harmful algal blooms continue to be a recurring problem, predominantly along the northeastern and mid-Atlantic coast of the United States, and in particular, in Southeast Asia (Nishida *et al.,* 2011, Hallegraeff, 1993). Agriculture is the largest source of nutrient pollution to coastal waters through leaching and runoff from fertilized land and animal waste. Crops do not absorb all the fertilizers applied and uptake efficiency varies regionally (Fixen *et al.*, 2014, International Fertilizer Association, 2019). As a consequence of high nutrient supply, mainly in the form of nitrogenous compounds, algal blooms are frequently observed in coastal areas. For instance, for the year 2019 the amount of about 194.5 million tons was used (International Fertilizer Association, 2019). The use of synthetic fertilizers has threatened the global environment and has called attention to the need of international action on how to mitigate the impact of nutrient release to the environment and its adverse effects on the terrestrial, freshwater and marine environment (United Nations Environment Assembly, 2019).

Monitoring with conventional methods the impact of anthropogenic nutrient release on a temporal and spatial scale is limited due to fast fluctuations under bloom conditions when phytoplankton develops within a short time and occurs in high concentrations. Due to time and spatial resolution limitations it is difficult to recognize in the offshore waters details on eutrophication through ship observations. The following study takes advantage of ocean color measurements by satellites that are now accessible over decades and allow for environmental inventories on a global scale (Behrenfeld *et al.*, 2006) covering vast areas as well as repeat measurements of chlorophyll and algal bloom at various spatial resolutions (Sathyendranath *et al.*, 2019). Therefore the primary objective of this study is to demonstrate that inter-annual changes in offshore chlorophyll can be related to land use practices and impact of environmental policies.

MATERIALS AND METHODS

Chlorophyll measurements

Remotely sensed chlorophyll data were analyzed over selected sites with data accessed from the System for Multidisciplinary Research and Applications (NASA Giovanni) that is developed for application in the analysis of Earth remote sensing for weather, climate, atmospheric composition, oceanography and hydrological processes. The data were displayed in image formats as well as digital data sets, and inter-annual observations were applied to linear fits. A comparison of all test sites was established with polynomial third-order fits. The time of observations covered January 2003 to December 2019 that resulted in a high density of observations at four-kilometer resolution. A detailed description of NASA's Giovanni is given by Acker *et al*., (2006).

Selection of Study Areas

Six sites were selected for comparison with varying degrees of anthropogenic emission and agricultural activities: the Amazon River estuary, the Yangtze River estuary, offshore Manila Bay, the New York Bight, offshore Chesapeake Bay and the Mississippi River estuary. The Amazon coastal area was selected because it can be assumed that at present, the region is least affected by industrial development and anthropogenic nutrient release. Therefore, changes in the Amazon offshore region should be minimal, and it is assumed that these changes are not significantly related to human activities although forest clearing and transformation of soil conditions through development of the agricultural sector have led to increased runoff and should also affect the nutrient budget. The Yangtze River was chosen for its enormous discharge and eutrophication is an increasing problem in the estuary as well as in the adjacent East China Sea (Chai *et al.*, 2009). In addition the Yangtze River discharge has been affected by the construction of the Three Gorges Dam and modification of agricultural practices in the upland are responsible for varying concentration of nutrients in the effluent. The near-shore region off Manila was chosen as a test site because of the highly populated areas around the semi-closed Manila Bay system. More than 10 million people live in the catchment area of the bay and Metro Manila has a population of about 12.9 million that contributes to a high nutrient emission with an increasing frequency of hypoxia and anoxia events in the Bay. The New York Bight was selected because over the years the offshore region was exposed to fluctuating nutrient levels from the Hudson River estuary, and environmental programs were introduced to reduce the nutrient flow through improved wastewater treatment. The Chesapeake Bay system is one of the largest estuaries in the United States and agricultural activities, sewage treatment plants, industrial facilities, and atmospheric fallout have contributed nutrients to high levels over the last few decades (Testa *et al.*, 2018). Mitigation efforts to reduce the nutrient flow were carried out over the years making the bay a good area to test for the efficacy of legislative action on nutrient control. The Mississippi offshore region was chosen because the river contributes about 90 percent of the freshwater loading to the Gulf of Mexico, and its outflowing water is known for developing eutrophication and build-up of hypoxia in the coastal region.

RESULTS

Figure 1A shows the investigated area of the Amazon estuary region and Figure 1B displays the average chlorophyll distribution that shows high concentration along the coast adjacent to the northwest flow of the Brazil Current that is recognized by low levels of chlorophyll. The monthly chlorophyll time-series in Figure 1C show a well-established seasonal cycle but the regression for all data does not exhibit a noticeable change during seventeen years.

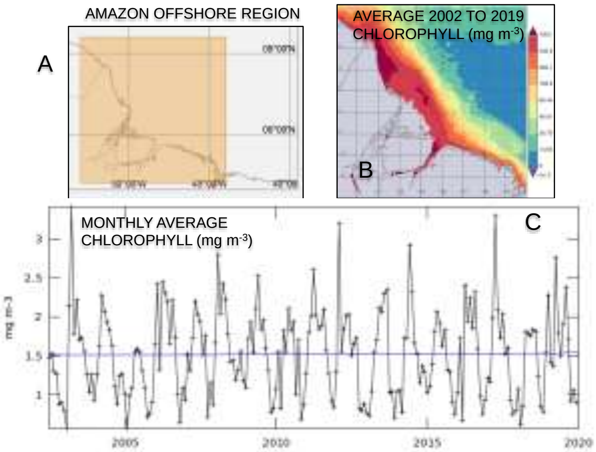

Figure 1: A. Location of observations in the offshore region of the Amazon effluent. B. Average distribution of chlorophyll for July 2002 to December 2019. C. Monthly averaged data for the same region in B.

The site selected site for the analysis of the Yangtze River plume is shown in Figure 2A and its extension can be recognized in Figure 2B with the average chlorophyll distribution while Figure 2C resolves the monthly changes with the linear regression demonstrating a decrease of chlorophyll during the time of investigation.

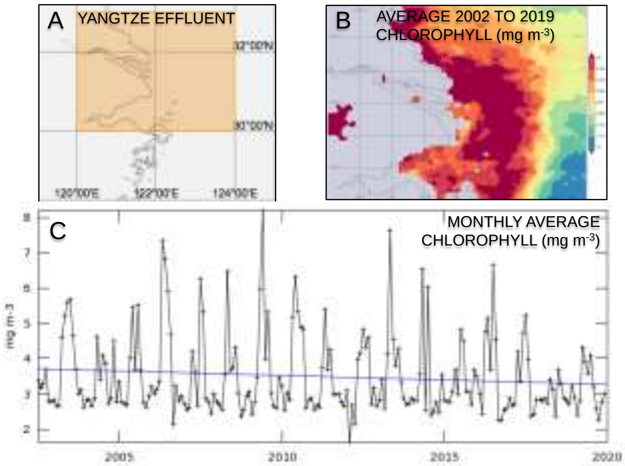

Figure 2: A. Location of observations in the offshore region of the Yangtze effluent. B. Average distribution of chlorophyll for the period July 2002 to December 2019. C. Monthly averaged data for the region in A.

The coverage of the region off Manila Bay is shown in Figure 3 and elevated chlorophyll concentrations reveal eutrophication as a result of the outflowing water from Manila Bay that is exported farther northwest along the Luzon coast. The monthly averaged chlorophyll series shows an intermittent maximum at around 2011 in chlorophyll that follows a decrease in the following years and less blooming is observed afterwards.

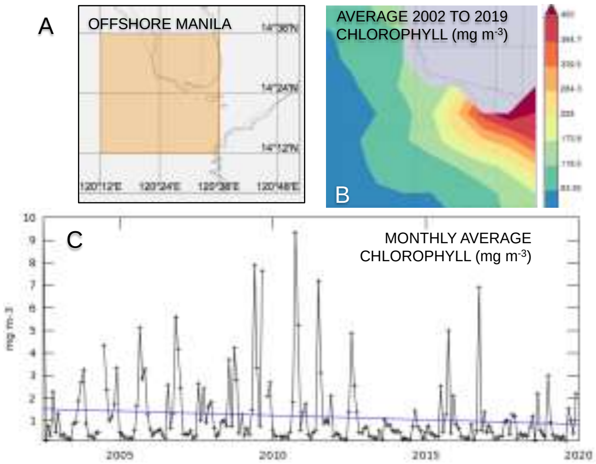

Figure 3: A. Location of observations in the offshore region of Manila Bay, B. Average distribution of chlorophyll for the period July 2002 to December 2019. C. Monthly averaged data for the same region in A.

Figure 4 shows the selected region in the New York Bight with the corresponding map of average distribution and monthly averaged time series of chlorophyll. A gradual decrease in concentration is observed from the coast and the monthly graphing of chlorophyll data resolves occasional bloom formation. Sporadic peaks are observed during the summer season especially after 2011. A linear trend-line indicates an increase during the period of investigation; however, the years after 2015 witness a reduction in magnitude of blooms. The yearly cycle in chlorophyll concentration is not well pronounced and is an indication that the offshore has an aperiodic supply of nutrients.

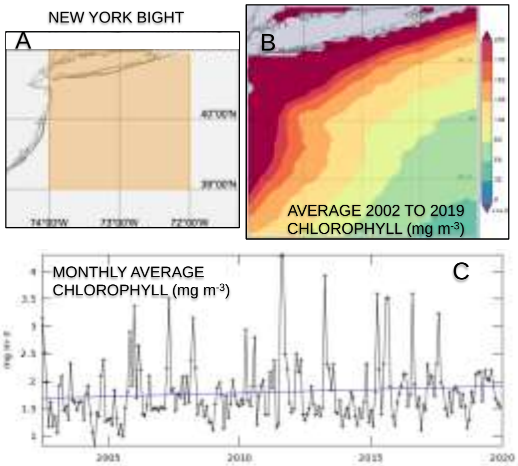

Figure 4: A. Location of observations in New York Bight. B. Average distribution of chlorophyll for the period July 2002 to December 2019. C. Monthly averaged data for the same region in A.

Figure 5 shows the selected region close to the Chesapeake Bay with the corresponding average map for chlorophyll distribution and the monthly time series. Figure 5B shows the sharp gradient that separates the coastal water on the continental shelf from the oligotrophic water from the Gulf Stream. The monthly data resolve the annual cycle of chlorophyll concentration and intermediate peaks are observed during summer. Compared to the New York Bight the concentrations are lower and the amplitudes of fluctuations are significantly reduced after 2013. Opposite to the trend line that was established for New York Bight, a decrease in concentration is observed in the Chesapeake offshore region.

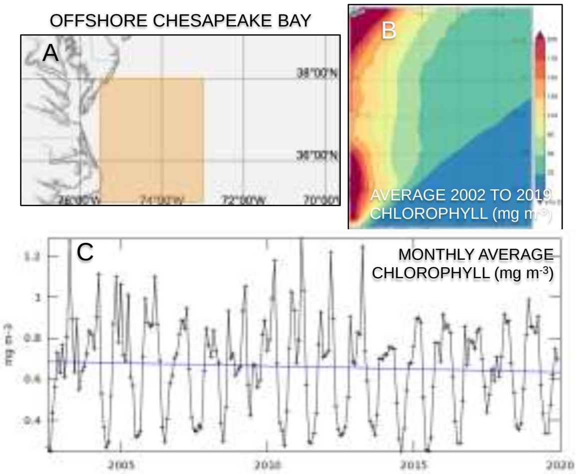

Figure 5: A. Location of observations in the offshore region of Chesapeake Bay. B. Average distribution of chlorophyll for the period July 2002 to December 2019. C. Monthly averaged data for the same region in A.

Figure 6 shows the analysis of the Mississippi site that reveals high concentration of chlorophyll in the coastal water. The monthly averaged data show a well-pronounced seasonal cycling and the trendline in Figure 6C documents a significant increase in chlorophyll during the time covered in this study.

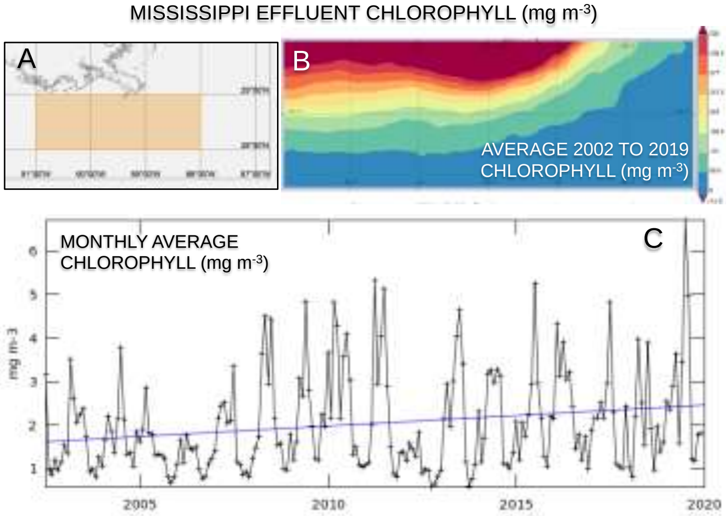

Figure 6: A. Location of observations in the offshore region of the Mississippi. B. Average distribution of chlorophyll for the period July 2002 to December 2019. C. Monthly averaged data for the same region in A.

The linear trend lines in Figures 1 through 6 provide a general view on changes in chlorophyll but do not reveal details on inter-annual fluctuations. Therefore the data from each site were separately subjected to a polynomial fit of which the results are shown in Figure 7. Based on the large data sets used in the analyses, it can be assumed that changes in slope of the polynomial trends are real and indicate environmental alterations.

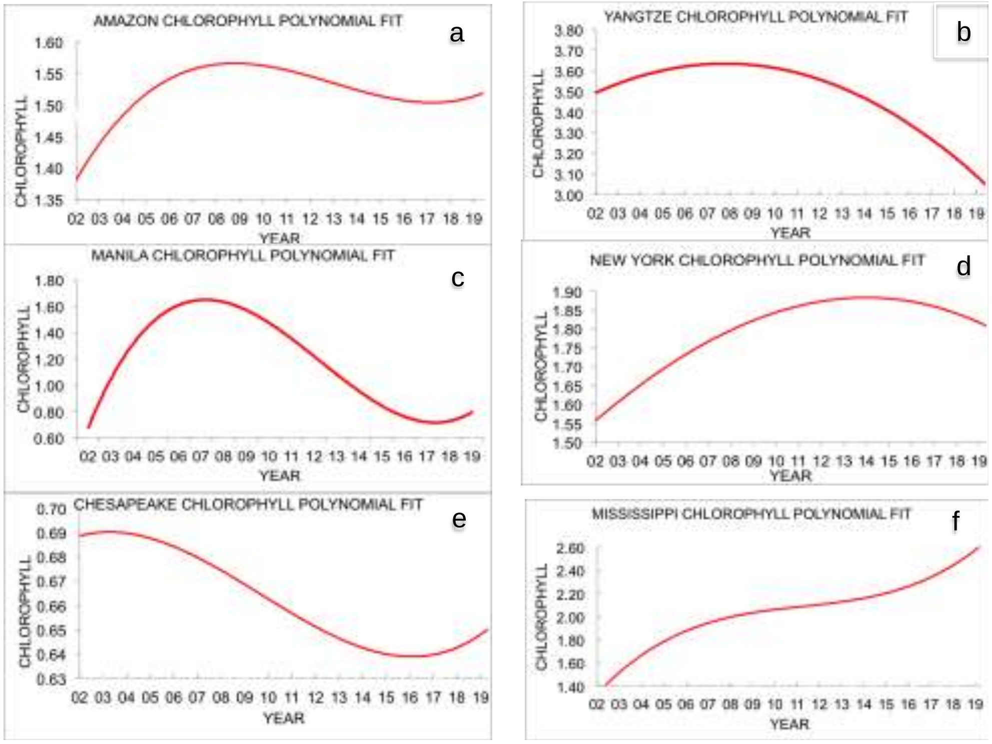

Figure 7: Polynomial fits of chlorophyll (mg m^{-3}) concentration for the six sites shown in Figure 1 through 6.

DISCUSSION

The time series and the polynomial fits of the data show for each site a different shape that is interpreted in the following as an outcome of land use changes and environmental policies. The results for the Amazon estuary region shown in Figure 7A indicate increasing chlorophyll values until 2008 but afterwards, the fluctuations in chlorophyll are only around 0.05 mg m^{-3} and the small changes seem to reflect the low impact of development in the Amazon basin. Compared to the magnitude of natural processes in the river system and the high discharge volume anthropogenic impact has at present no significant influence (Smoak *et al.*, 2006). The primary reason is that the population along the Amazon basin is relatively low, and one can assume that there is only minor nutrient emission from industrial processes. However, land-use change affected around 20 percent of the Amazon basin with a peak of deforestation in the Amazon around 2004 that followed a 76 percent decline in deforestation rates as of 2018 (Marengo *et al.*, 2018). Therefore, at begin of the 21st century increased nutrient release could have been the consequence of enhanced soil deterioration from deforestation and consequently increased chlorophyll concentration.

The offshore changes in chlorophyll for the Yangtze effluent region have to be viewed against the decade-long application of fertilizers that was promoted by the Chinese government, and as a result farmers used more than four times the global average of fertilizers and are the cause for eutrophication and unusual plankton blooming in the near-shore region. However, starting in 2005, agricultural practices changed and in the following years, fertilizer use was reduced by around 15-18 percent (Hauptman, 2018) that reflects also the changes in the chlorophyll trend at around 2007. Furthermore, one has to consider the important alteration of the hydrography in the Yangtze River that began with the construction of the Three Gorges

Dam and led to reduced flow, less river sediment load and lower nutrient flux. A comparison of nutrient data and potential nutrient limitation of phytoplankton growth before and after impoundment of the dam in 2003 showed that concentrations of nitrate and dissolved phosphorus in the upper estuary of the Yangtze increased from 1980 to 2006 while the area of potential phosphorus limitation expanded after 2003 (Chai *et al.*, 2009). These observations indicate that the chlorophyll decline is in response to reduced nutrient transport as shown by the change of slope in Figure 7b.

The high chlorophyll concentrations in the vicinity of Manila Bay are the result of nutrient input that originates from the discharge of nutrient and unprocessed liquid and solid waste that enters straight into the river system. Related to the high discharge of nutrients from the various sectors are outbreaks of red tides and other harmful toxic algal blooms in coastal waters with an increasing frequency in Manila Bay (Tirado and Bedoya, 2008; Wang *et al.*, 2008; Soto *et al.*, 2015, Szekielda, 2013)). Furthermore, due to the rapid increase in population and industrialization in the watershed, the water quality deteriorated through excessive urban emissions of nitrogen and phosphorus compounds that led to higher frequencies of harmful microalgae and persistent red tides. In response to this detrimental development, the Pasig River Rehabilitation Commission (PRRC) was established to oversee rehabilitation efforts for the river although nutrient load to Manila Bay may not decrease with better sewage treatment because of the high population growth. The peak of eutrophication in the investigated offshore region appeared around 2007 and declined until 2017. The adoption of integrated coastal zone management around Manila Bay most probably contributed to the decline of nitrate and phosphate concentrations in Manila Bay. This is evident when averaged data from 1993 to 2004 are compared with recent nutrient concentrations (Jacinto et al., 2006).

Figure 7d shows the polynomial fit for chlorophyll data in the New York Bight that reveals a reduction in chlorophyll concentrations after reaching the maximum concentration at around 2014. The changes can be attributed to the response of integrating environmental goals and legislative action that followed the Ocean and Great Lakes Ecosystem Conservation Act and the Coastal Zone Act Reauthorization Amendments. New York City is processing daily about 4.0 billion liters of wastewater, and in addition, the outflowing Hudson River is subjected to occasional sewage overflow with more than 7.6 billion liters that were released into the Hudson River at one occasion (Shapley, 2019).

The polynomial fit for the offshore region in the vicinity of Chesapeake Bay is shown in Figure 7e. From 2004 to 2016 a steady decline in chlorophyll concentrations is observed that is followed by a slight increase. The region has long been subject to the appearance of marine dead zones where low oxygen concentration are an outcome of the high load of nitrogen and phosphorus to the Bay and formation of algal blooms (Kemp *et al.,* 2005). The observed decline in offshore chlorophyll concentrations has to be viewed against the long-lasting strategies that were introduced to lessen the impact of nutrient transport into the Chesapeake Bay. Nutrient and oxygen measurements in Chesapeake Bay for the last several decades showed that late-summer hypoxia in the estuary declined slowly by about 1 percent per year which has been attributed to the gradual reductions in nitrogen loading for two decades (Testa et al., 2018). Starting in 2018 with new nutrient pollution-reducing practices about 39 percent of the nitrogen and 77 percent of the phosphorus reductions were achieved. Compared to 2009 levels, the Chesapeake Bay Management Strategy (2017) was in the position to report nutrient reduction in the Bay of 40 percent nitrogen and 87 percent phosphorus. Compared to the 2009 baseline established by the U.S. Environmental Protection Agency (Chesapeake Bay Management Strategy, 2017), the resulting nutrient level changes are also indicated by the offshore chlorophyll signals and seem to manifest a good response to legislative actions taken to reducing nutrients in the Chesapeake Bay.

Chlorophyll concentrations in the effluent of the Mississippi show a steady increase in chlorophyll concentration that can be related to the nutrient transport through the river. During 2000–2014 the export of total nitrogen was twofold larger than that in the first decade of the twentieth century, and dissolved inorganic nitrogen export increased by 140 percent, dominated by nitrate and total organic nitrogen (Tian *et al.*, 2020). Historical data show that oncentrations and loadings to the adjacent continental shelf accelerated since the 1950s to 1960s (Rabalais *et al.*, 2001; Rabalais *et al.*, 2002). Furthermore, nutrient transport to the coastal area has modified the natural nutrient balances, and in particular, the stoichiometric nutrient ratio in the adjacent continental shelf system (Rabalais *et al.*, 1996). The problem in mitigating eutrophication in the Mississippi coastal region is that significant deforestation, conversion of wetlands and expansion of artificial agricultural drainage removed most of the Mississippi basin's natural capacity to withhold nutrients from runoff draining into the Mississippi system (Rabalais *et al.*, 2002). Long-term monitoring of the country's streams and rivers by the U.S. Geological Survey has also shown that nitrogen loading into coastal estuaries has been increasing (Pellerin *et al.*, 2014). The nutrient flow continued to increase in 2019 that contributed nitrate to the Gulf by 18 percent above the average from 1980-2018, and total nitrogen load was 19 percent above the average from 1980-2018 while total phosphorus and dissolved silica loads were 49 and 69 percent above average, respectively (NOAA Press Release, 2019). The increase of chlorophyll as shown in Figure 7f follows this development and demonstrates that amid legislative restriction on nutrient load to the river, the already elevated chlorophyll levels are still increasing.

The foregoing examples show changes in offshore chlorophyll concentrations that are interpreted as an effect of anthropological nutrient input from upstream to the riverine environment and coastal regions. It can be generalized that in order to detect the effects of legislative measures through chlorophyll measurements in the offshore regions, large data sets with time series are required as has been demonstrated with selected examples in this study. In particular the data from the Yangtze River and the Mississippi region give strong evidence that the eutrophication offshore signal documents not only the effect of nutrient discharge but also the influence of nutrient application and changes in land use practices. However superimposed to those changes are physical and biological processes that are mainly based on global temperature changes. Thus the anthropogenic signal has to be discussed in future research in connection with global change in the marine ecosystems in order to separate the two processes. Furthermore, research on this relation has to be refined with adequate and standardized site locations and a continued monitoring over longer time and defined space scales.

ACKNOWLEDGEMENT

Analyses and visualizations used in this study were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

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