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Research Article

SCALE OF EUTROPHICATION IN COASTAL WATERS

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ABSTRACT
The effects of eutrophication are undesirable and may be considered a form of pollution through excessive production of algal material. Eutrophication develops at various time-space scales and remote sensing data were applied in this study to determine the size and life span of algal blooms. Examples from different regions show that patchy distributions of algal blooms occur over several orders of magnitude on a horizontal length scale. An approximation was made of the patch sizes in relation to their observed life span. It shows that in coastal settings patch size is in the neighborhood of hundreds of meters and they have the expected low life span, whereas mesoscale eddies are in the range of 10 to 100 km with a possible life span of months.

Keywords: *Eutrophication, Remote Sensing, Algal Blooms, Patch Size, Life Span*

INTRODUCTION
Coasts and estuaries are the most valuable resource areas that provide access to fish and shellfish production as well as recreational and infrastructure development. With increasing population, external pressures in the coastal zone and increasing emission of anthropogenic products, a threat emerges to modify the ecological functioning of the coast. As a result of the human impact, eutrophication through nitrogen pollution accelerates changes along the coasts and in the oceans of the world and is regarded as one of the greatest consequences of human accelerated global change (Howarth and Marino, 2006; Smith, 2006).

Eutrophication is described as the natural or artificial addition of nutrients to bodies of water and to the subsequent effects of the added nutrients (National Academy of Sciences, 1996). When the effects are undesirable, eutrophication may be considered a form of pollution and such is the case when waters high in nutrients lead to excessive plankton production and occasional blooming of algal material. A more general and broader definition is that eutrophication is a process where bodies of water, such as lakes, estuaries, slow-moving streams and coastal regions, receive excess nutrients that stimulate excessive plant growth.

Intense blooming can lead to decomposition of dying algae and oxygen uptake through respiration that result in the depletion of oxygen in the water. Those conditions lead to death of organisms that depend on a certain oxygen level in the water column.

Nixon (1995) pointed out that research on coastal eutrophication has progressed only in recent decades. He referred to eutrophication as an increase in the rate of supply of organic matter to an ecosystem that might be initiated either from external sources or from production within the system through biological processes.

It is generally assumed that all populated coastal regions are affected by the appearance and development of harmful algal blooms and that more toxic algal species impact fishery resource compared to several decades ago.

The reasons for this environmental change include natural dispersal of species by currents and storms, dispersal of species through human activities and eutrophication through supply of nutrients from point and non-point sources (Anderson *et al.*, 2008). Eutrophication is to a high degree the result of the increasing need to enlarge the carrying capacity for a growing population coupled with the increasing use of fertilizers.

For example, in the Philippines application of fertilizers in farming increased by 1000%, while the major staples like rice and maize increased only by 200 and 280%, respectively, and others remained approximately about the same. This indicates that a high portion of applied fertilizers results in a loss to the aqueous phase, leading to water pollution with detrimental effects on human health. This scenario is found worldwide, and in response to excessive nutrient loading into coastal waters, the presence of harmful algal blooms (HABs) can have far reaching consequences that may lead to paralytic shellfish poisoning (PSP), a recurring problem along the northeastern part and mid-Atlantic coast of the United States and in particular in Southeast Asia (Nishida *et al.*, 2011).

Hallegraeff (1993), showed that virtually every coastal region is affected by harmful algal blooms. Snickars *et al.*, (2015) found that throughout the 1980s, increasing benthic-feeding fish that are in abundance in shallow waters of the Baltic Sea was primarily attributed to eutrophication. Eutrophication and climate change are even considered now as the major drivers that may potentially change productivity of coastal ecosystems.

Parallel to the increase of food production is an increase in the use of fertilizers. At present, China is number one in consumption of fertilizers followed by the United States. It is anticipated that this trend will not change in the near future.

Eutrophication in near coastal waters as the response to augmented nutrient supply, is mainly controlled by vertical mixing rates, stratification of the euphotic zone, and the irradiance at the sea surface. Modifications of these forcing factors may result from changes in surface circulation that defines the location and boundaries of provinces with varying primary productivity. Furthermore, algal blooms can be impacted by horizontal and vertical displacements as well as by turbulent mixing and tidal action. The complexity of these processes is especially evident in estuaries where river and ocean environments act together (Glibert and Burkholder, 2006).

In the United States, the mid-Atlantic coastal region is apparently the most affected by eutrophication as pointed out by Bricker *et al.*, (2008). For example, increasing nutrient discharge through the Chesapeake Bay and the Albemarle-Pamlico Estuarine System is mainly a result of increasing human population, change in land use and nutrient load due to growing animal populations, and consequently, an increase also of nitrogen-based fertilizers (Kemp *et al.*, 2005), and up to about 80% of NH_3 originate from swine operations in North Carolina (Aneja *et al.*, 2003).

This shows that the magnitude and duration of blooms in bays and inlets is controlled significantly by anthropogenic nutrient emission.

However, the initiation of large-scale HABs along open ocean waters appears to be unrelated to anthropogenic nutrients, since nutrients supplied by upwelling or advection from offshore water masses or by N_2 fixed from co-occurring blooms can be dominant compared to inputs from land and atmospheric sources (Anderson *et al.*, 2008; Anderson, 1997).

Eutrophication develops at various time-space scales that result in patchiness and physical appearance of blooms that in most cases cannot be resolved with conventional ship operations. In response to this shortcoming, remote sensing techniques are frequently applied as an additional tool for estimating the concentration of plankton and to determine the size and life span of a bloom. However, remote sensing data, when interpreted in terms of plankton, are not vertically resolved and are heavily weighted towards the surface.

Consequently, the interpretation of recognized bloom patterns needs to take into account, therefore, that algal concentrations derived from remote sensing represent only a composite of various pigments from optically weighted concentration of the upper portion of the water column (McClain *et al.*, 1993).

In addition, to recognize patterns and extent of bloom conditions, high spectral resolution of remote sensing allows to identify spectral regions where absorption of various photosynthetic pigments takes place.

As shown with spectral data in Figure 1, the well-pronounced *in vivo* chlorophyll absorption band and other accessory pigments that are associated with plankton, influence the shape and intensity of the spectrum that can be indicative for the character of bloom conditions.

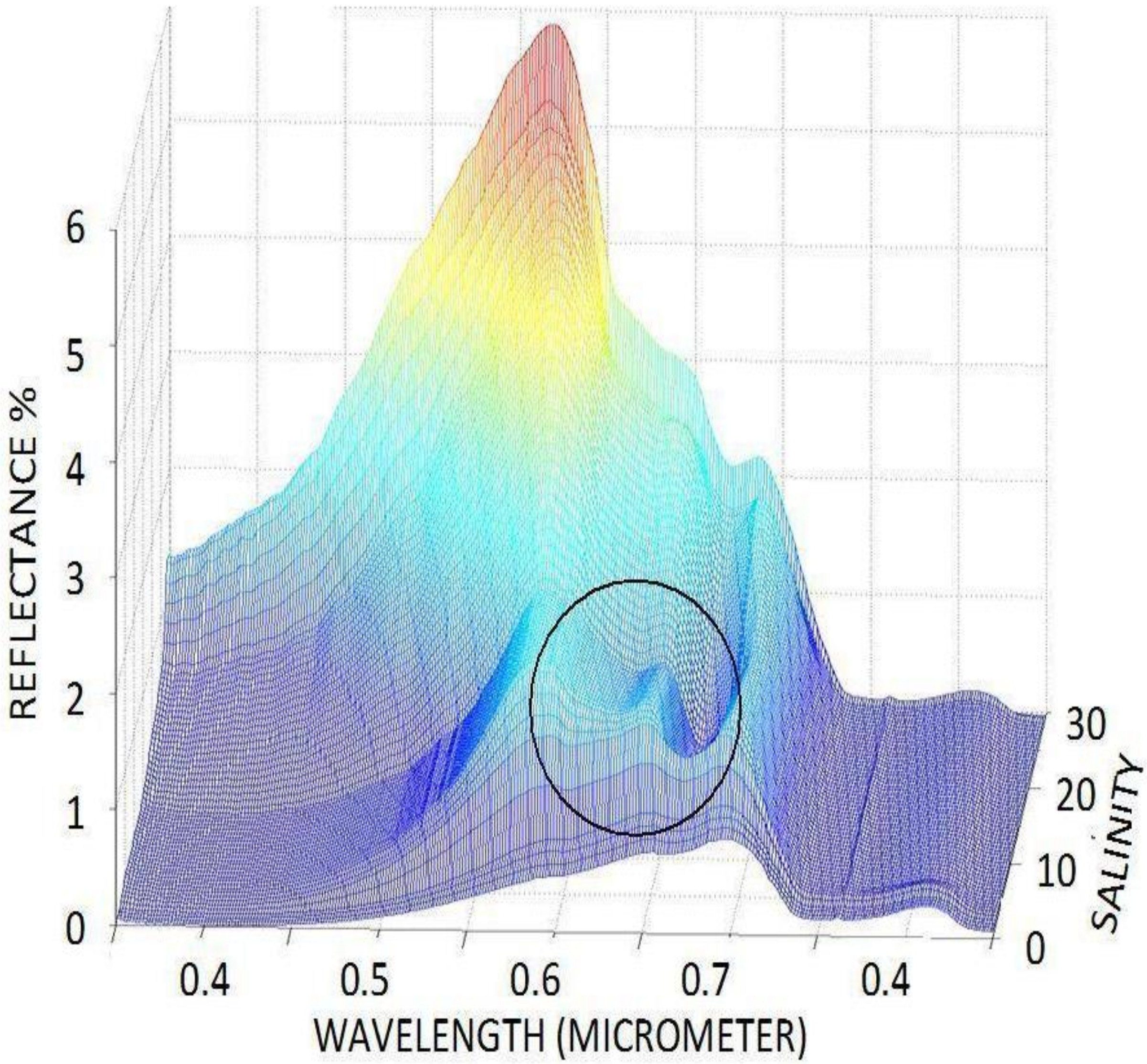

Figure 1: Relationship of spectral reflectance and salinity in eutrophic water. The encircled spectral region shows the region where *phycocyan* as a photosynthetic pigment in cyanobacteria was identified. The spectral region between 0.4 µm and 0.5 µm is characterized by strong absorptions of chromophoric dissolved organic material, carotenoids and chlorophylls. Minimum absorption is observed in the range of 0.550 µm to 0.570 µm that results in a reflectance peak mainly due to scattering by phytoplankton cells and organic as well as inorganic particles. Eutrophication is evident at salinities around 15psu and is characterized by the strong absorption between 0.600 µm and 0.700 µm with the distinctive second chlorophyll absorption band located at 0.670 µm.

Spatial Observations of Plankton Blooms

Scales on which conservative parameters in the coastal ocean appear and distributed are a function of the controlling dynamics, whereas non-conservative parameters can also be impacted by chemical and biological processes. The dynamics of marine processes occur over several orders of magnitude on a horizontal length scale that may range from millimeters to about 1000 kilometers. Typically, ocean currents are on a spatial scale between 10 to 100 kilometers whereas a scale of a meter range appears in near-shore waters. Therefore, the resolution capability of a remote sensing device has to be selected according to the spatial and temporal dimensions of a bloom as is illustrated with examples in Figure 2.

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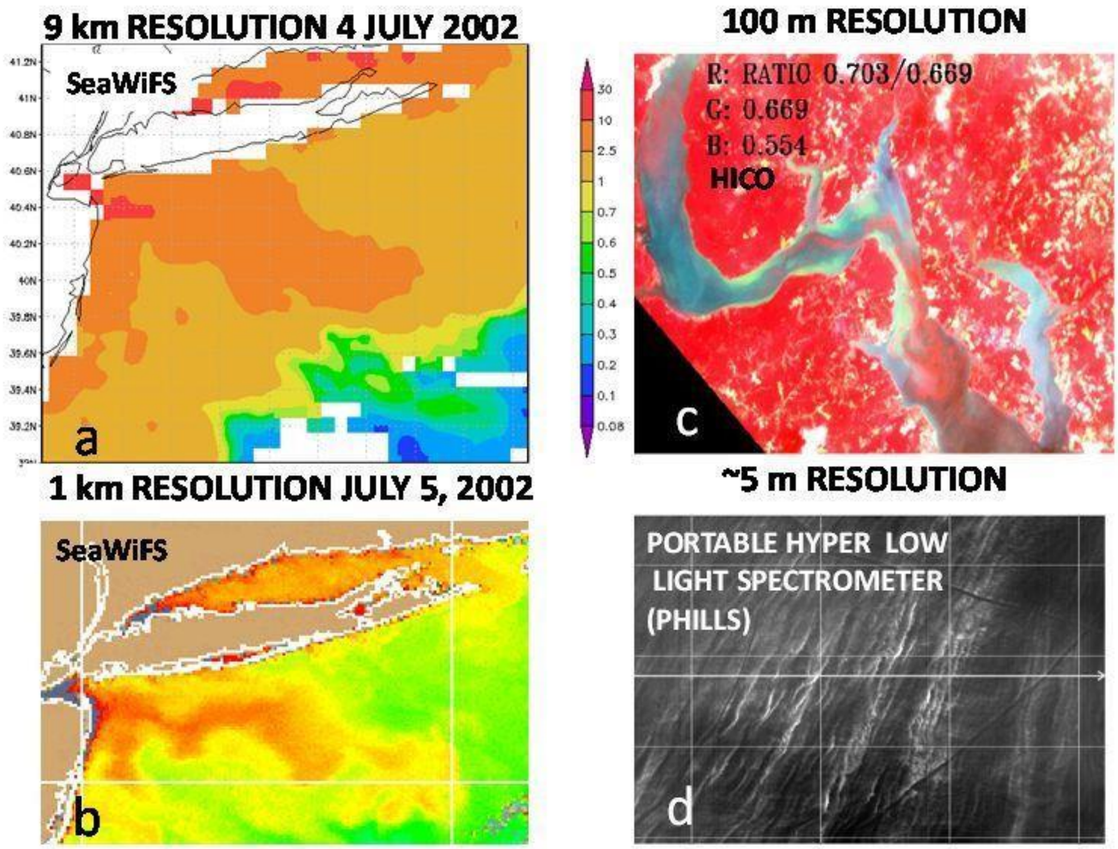

Figure 2: Plankton patches observed with varying ground resolutions.2a: Chlorophyll patch in the vicinity of the discharge area of the Hudson River, New York Bight observed with MODIS at a ground resolution of about 9 km. 2b: The same region as in 2a,except one day later, observed with MODIS at a ground resolution of about one km. 2c: Observation with the Hyperspectral Imager for the Coastal Ocean (HICO) of a *Microcystis* bloom in the lower Potomac River at a ground resolution of about 100 m. 2d: Langmuir circulation observed in a *Microcystis* bloom in the lower Potomac River. Data were recorded from aircraft altitude at a ground resolution of about five meters.

Coarse resolutions applied in Figures 2a and 2bare sufficient for large-scale inventories whereas detection of eutrophication in geographically restricted waters, like lakes, rivers and smaller bays would require a resolution of around 100 m or less (Figure 2c). Some processes are responsible for uneven but structured distribution of plankton as is the case for Langmuir circulation which would require for its detection a ground resolution in the meter range (Figure 2d) because algal accumulation appears in narrow, linearly built convection cells. Those cells develop at wind speeds of around 3 m $sec^{-1}$and can be recognized as an array of subsurface counter-rotating vortices, or cells, that are aligned approximately parallel to the wind that are only a few meters apart. The development of Langmuir circulation in response to the wind is in the neighborhood of only 30 minutes and the creation of new streaks is consistent with the advection time of surface material into windrows (Szekielda *et al.,* 2007). Although processes at a smaller time/space ranging down to molecular diffusion may play an important role in plankton development, Langmuir circulation seems to be one of the processes that has significance for understanding the dynamics in the distribution of algal material near the air-sea interface.

Smaller bays and estuaries display blooms on a specific time-space scale and an example of eutrophication and bloom development is given with the Peconic Bay of Long Island in the United States. The bay is an estuarine environment with nutrient gradients from tidal creeks in the western region to meso-trophic bays in its eastern region and eutrophication takes place in the vicinity of river out flows where discharge of nutrients from wastewater treatment is present. Such small estuaries are subject to fast fluctuations developed by wind stress and tidal action, both preventing long-term column stability and significant stratification throughout the whole year.

The difficulty in detecting blooms and their extent with conventional methods is due to their horizontal and vertical heterogeneity in distribution. For instance, phytoplankton organisms can appear at the surface as dense blooms that may aggregate to form surface scum and produce surface-active compounds. Accumulations of organisms at the air-sea interface may also be expected in those regions where tidally driven convergence fronts and convergence zones that are associated with Langmuir circulation cells appear. Finally, some organisms are even able to regulate their buoyancy with gas vacuoles and are thereby able to change their vertical distribution pattern within a very short time interval. Dense blooms, therefore, can exhibit rather complex distribution patterns as can be demonstrated with examples in Figures 3a, b, c, and d.

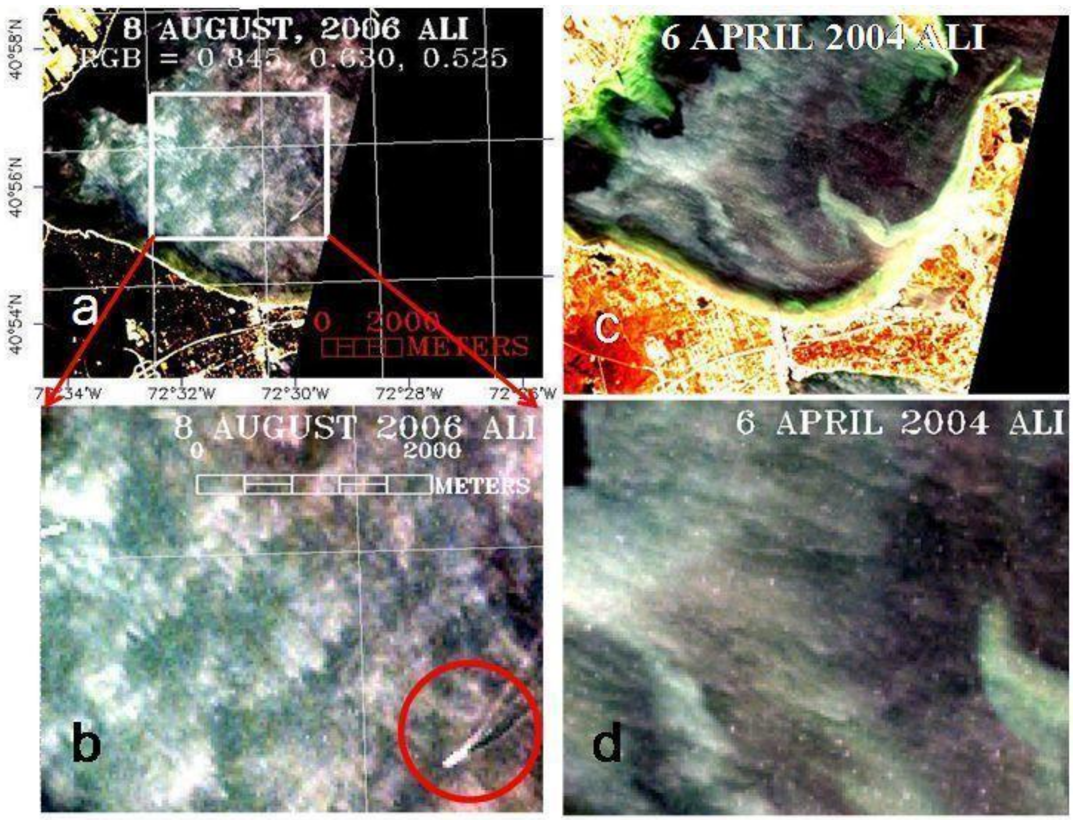

Figure 3: Image with a 30m resolution from the Advanced Land Imager (ALI) were merged with a 10 meter panchromatic band and presented as RGB. Images are for August 8, 2006 (3a) and April 6, 2004 (3c). The lower images 3b and 3d are the corresponding zoom images indicated in the white square in 3a.The ship wake shown in 3b, in the red circle, indicates that the observed blooming is close to the surface because low radiance is observed behind the ship wake where water mixes from below to the surface through propeller action. High plankton concentrations were confirmed with observations of *Cochlodinium* that appeared for the first time in July, and were reported for August through September at cell densities around >10^4 ml^{-1}.

Bloom conditions may appear in restricted bay environments at short time scales, and bloom conditions may not even be fully observed with ship observations as can be demonstrated in Figure 4 with a comparison of chlorophyll measurements derived from ship and satellite data. It is evident from the data that the more frequent observations with satellites showed more blooming events than the observations taken from ships which means blooms may go undetected if the observations are not phased with the appearance of bloom conditions. Furthermore, under bloom conditions, wind stress may change the distribution of organisms close to the surface within a very short time frame, with occurrences of less than one hour, which has been observed with repeat aircraft flights over cynanobacteria blooms in the Potomac River (Szekielda *et al.*, 2006).

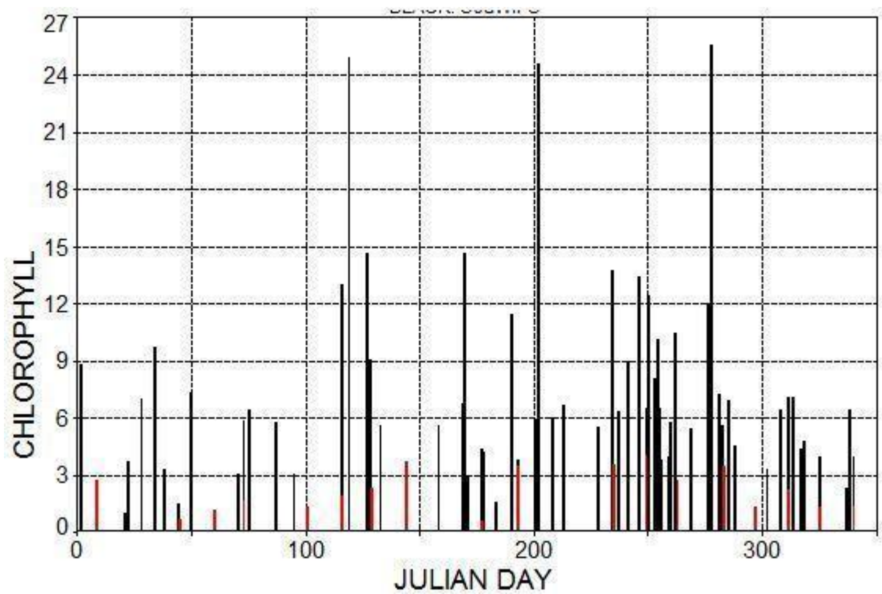

Figure 4: Comparison of chlorophyll concentrations (mg m^{-3}) in the center of Peconic Bay for the year 2001 derived from Sea WiFS (in black) and ship observations (in red)

Bloom conditions in the Great Peconic Bay occur frequently and a bloom with a horizontal extent of several kilometers that coincided with ship observations of a dinoflagellate bloom *(Coclodinium polykrikoides*, Gobler *et al.*, 2008) was observed and is shown in Figure 5.

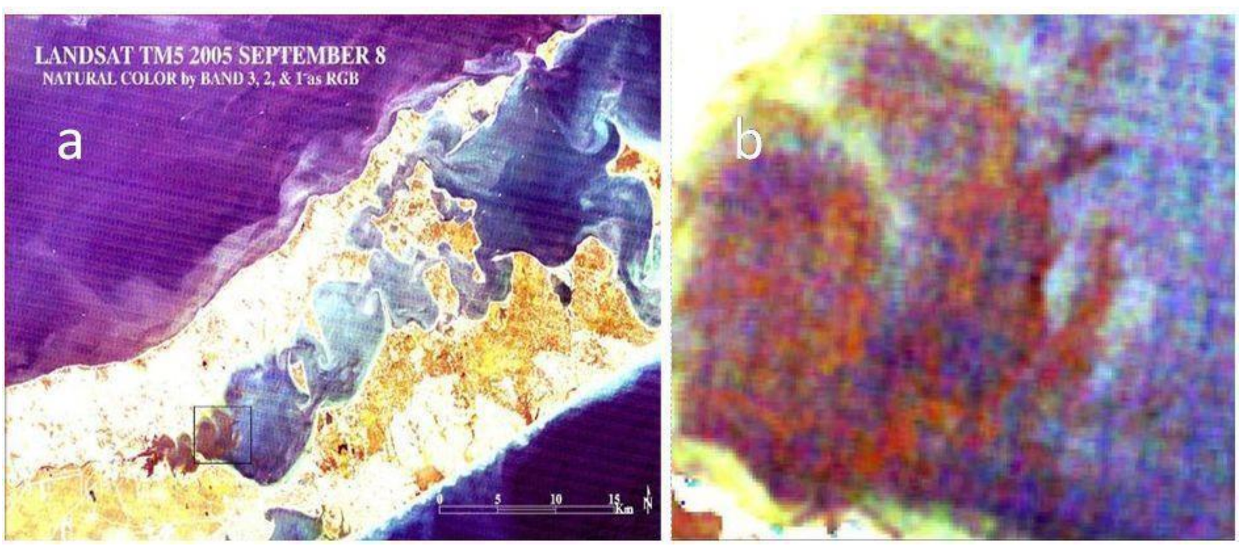

Figure 5: Observation of a bloom in the eastern part of Great Peconic Bay based on Landsat TM5 on September 8, 2005 at a time when flood starts. The area in the rectangle in Figure 5a indicates the image shown in Figure 5b.

Aside from wind action, currents may modify the distribution pattern of algal material within a very short time frame, and in particular, during the tidal cycle. Data from the Peconic Bay have indicated jets and swirls that are created in relation to water passages through channels at the entrance of the bay. Strong incoming currents form a frontline where denser water enters from the bay as a plunging front and is interpreted as the formation of a leading internal wave.

Frequency and intensity of bloom development depend not only on the flux of nutrients to the system but also on the residence time or flushing of water through a coastal system. Larger water bodies that are not subjected to tidal flow or that are oceanographically separated to build an adjacent sea, show limited exchange of water, which may lead to an accumulation of nutrients and blooming conditions. Such conditions exist for example, in the Sea of Azov and the Baltic Sea (see Figure 6) that shows vertical stratification of water masses caused mainly by salinity gradients and during the summer season by temperature as well.

This stratification restricts vertical circulation and supports the consequential entrapment of nutrients. It was estimated that the Baltic Sea contains at present about 800% more phosphorus compared to 100 years ago (HELCOM, 2009).

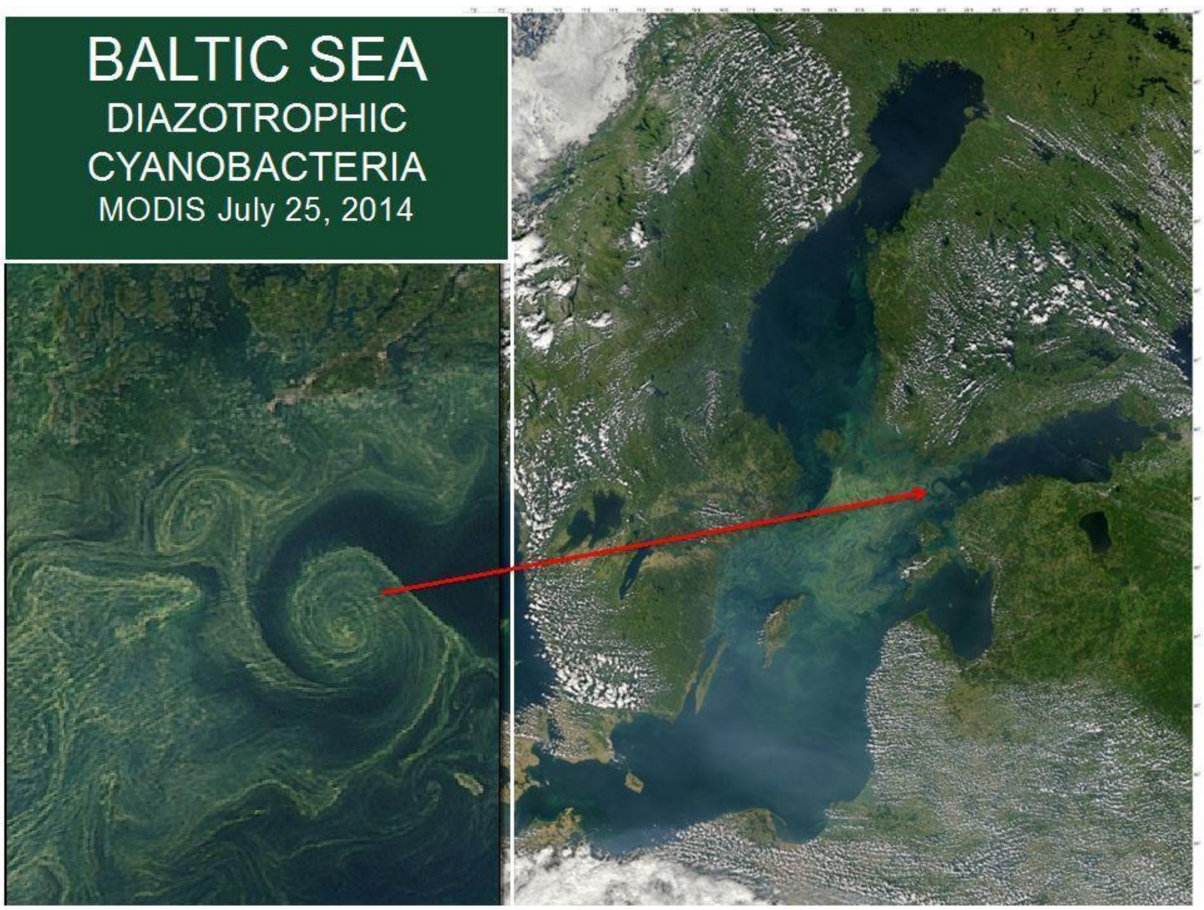

Figure 6: Massive blooms of *diazotrophic* cyanobacteria in the Baltic Sea on 25 July 2014 recorded by MODIS (NASA Goddard Space Flight Center)

The combination of high residence time of water and nutrients discharged to the sea may remain sometimes for decades, before being flushed out of the Baltic Sea into the Skagerrak surface waters. In 2000, eutrophication in the Baltic Sea, reached a magnitude of about 660,000 tons of nitrogen and 28,000 tons of phosphorus discharged into the Baltic Sea via the rivers. This is about four times as much nitrogen and eight times as much phosphorus compared to the early 1900s (HELCOM, 2009).

High nutrient discharge is symptomatic for highly populated coastal areas and almost all coastal megacities are exposed to reduced water quality and development of HAB. Manila Bay, for example, is surrounded by an area with high population of about 10,000,000 residing mainly in the catchment area of the Bay.

Agriculture, forestry and fishery are responsible for rising emission of nutrients that increase the frequency of hypoxia and anoxia events (Chang *et al.*, 2009). Plankton bloom occurrence for the Manila coast is frequently observed (Reyes and Bedoya, 2008) and outbreaks of red tide and other harmful toxic algal blooms indicate an increasing frequency in Manila Bay and its neighboring waters (Wang *et al.*, 2008). Information on the decoupling of eutrophication from the monsoon seasons was documented with satellite chlorophyll measurements (Szekielda *et al.*, 2014).

Large rivers have the capability to carry nutrients far into the offshore region based on the discharge of nutrients directly from drainage areas. While smaller effluents may have only limited impact on the coastal environment, large river discharge can influence offshore water to a high degree. This is demonstrated with the Yangtze River effluent that strongly regulates the coastal environment by its discharge of freshwater and sediment towards the South China Sea.

The resulting extensive eutrophication is shown with an example of the Yangtze River plume in Figure 14 that has wide spacing and can occasionally be tracked by following the salinity of less than 30 psu in the offshore direction to about 100 km from the coast in summer and about 50 km in winter (Limeburger *et al.*, 1983).

The high level of eutrophication developed in the river effluent is based on excessive use of fertilizers that are applied in China but are not fully converted to biomass as only one-third of the three million tons of fertilizer used are actually absorbed by crops (Wu, 2011).

It can be concluded that the largest portion of the non-converted fertilizer is eventually discharged into rivers, lakes and finally may enter the coastal region. As a result, frequent plankton blooms are observed within the effluent of the Yangtze River estuary as well as in the adjacent East China Sea (Chai *et al.*, 2006), and harmful algal blooms may cover thousands of square kilometers in the area off the Yangtze River estuary (Lü *et al.*, 2007).

The coastal areas that are exposed to eutrophication cited in the foregoing examples are only a few of the many effected regions. However, the selected sites show the complex distribution patterns of plankton blooms and the problems that arise in estimating the significance of a plankton patch and its life span based on image material alone.

Mullin and Brooks (1977) pointed out that the lifespan of a plankton patch during bloom conditions, and its non-uniformity as well as its spatial variability are the main factors in the persistence of ecological dynamics.

One also has to consider as well the physical and biological processes that may occur on very short or intermediate time scales rather than those that are recognized on the kilometer scale. The different processes acting on a patch make it difficult to estimate the lifespan of an observed patch. That means that the time and space frame of a patch also has to include the vertical displacement of phytoplankton caused by turbulent mixing, internal waves, Langmuir circulations, current shear as well as the nutrient transport from below the euphotic zone.

If the color domain of a bloom is included in the interpretation of remote sensing data, the spectral properties contribute an additional cause for patchiness because the spectral response of a bloom is not only related to concentration but also to the depth location of algal material. This indicates that at the same concentration but different depth location, the spectral response of a plankton patch may appear optically very different. Therefore, based on its spectral properties alone, it can be assumed that a portion of a given bloom patch can appear at different space and time scales. Patchiness in the spectral dimension can be illustrated with an image in Figure 7a that was classified based on spectral responses of pixels in the image. The patchiness in this example was generated by an input of nine different reflectance spectra and demonstrated that patchiness occurs at various sizes and according to the number of spectral inputs to the classification process.

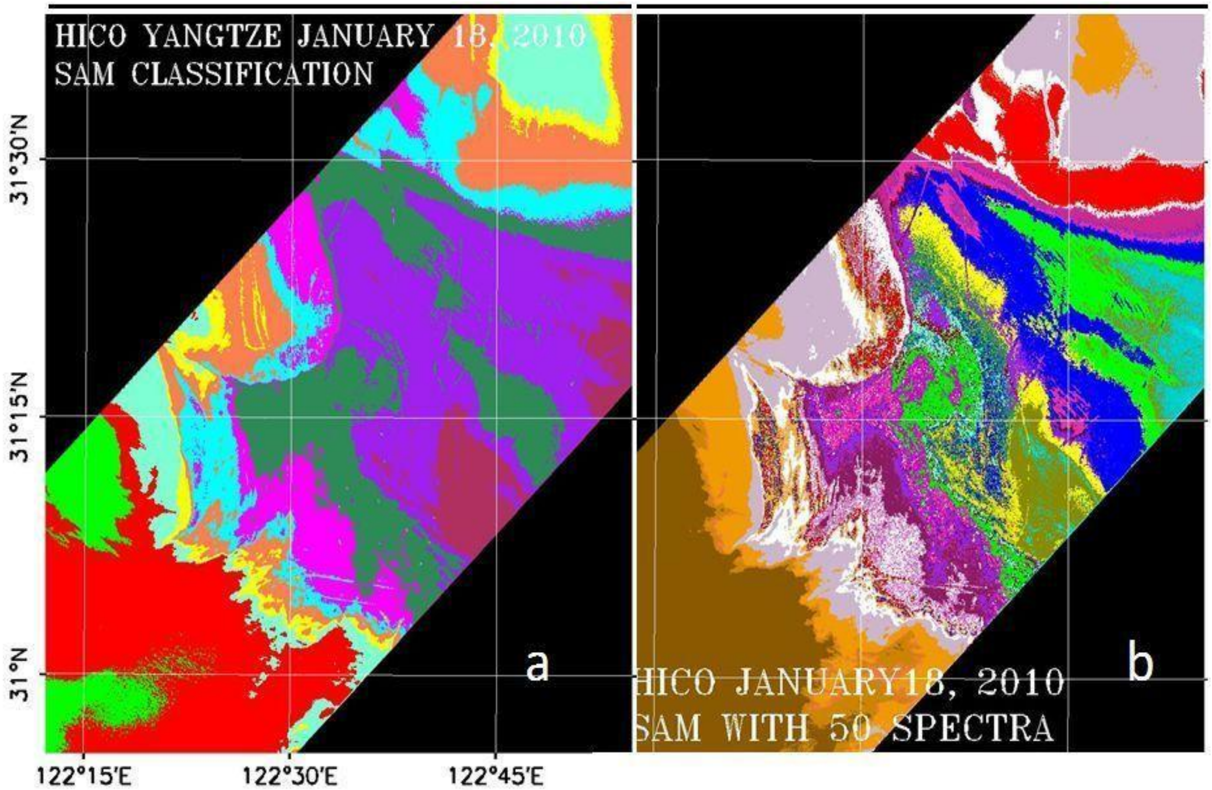

Figure 7: Supervised classification of the area of the Yangtze River outflow as recorded by HICO. 7a had nine spectra as an input to show nine patches whereas 7b had50 spectra as an input to create the corresponding number of patches. Modified from Szekielda *et al.*, (2013)

The impact of defining spectrally a patch appearance is shown in Figure 7b for which additional spectra were used that led to detecting a higher complexity of patches. The result shows that in principle, patch sizes may occur over a higher frequency range.

Although such small patches can be present in a natural surroundings, they may follow a very low time-space scale relationship.

Considering the optical response of plankton and other colored material in the water, patchiness can appear as a single picture element and may be regarded as the smallest patch because it can be assumed that the spectral response of neighboring pixels differ.

CONCLUSION

The significance of patchiness at such scales may be of minor importance in oceanic water but an estimate for the relationship between larger patch sizes and their lifespan might be of interest. A qualitative approach to estimate such a relationship is based on repeat observations of patches by remote sensing and conventional methods in various environmental settings.

The results shown in Figure 8 give an approximation of the life span of naturally generated patches in relation to their observed patch sizes.

It follows that in a coastal setting, patch size in the neighborhood of hundreds of meters have the expected low life span despite the fact that they may promote an environment suitable for increased primary productivity.

The diagram covers also the lower patch size that is generated by vertical turbulent mixing. Mesoscale and shorter time scales are in the middle range where eddies and fronts are in the range of 10 to 100 km.

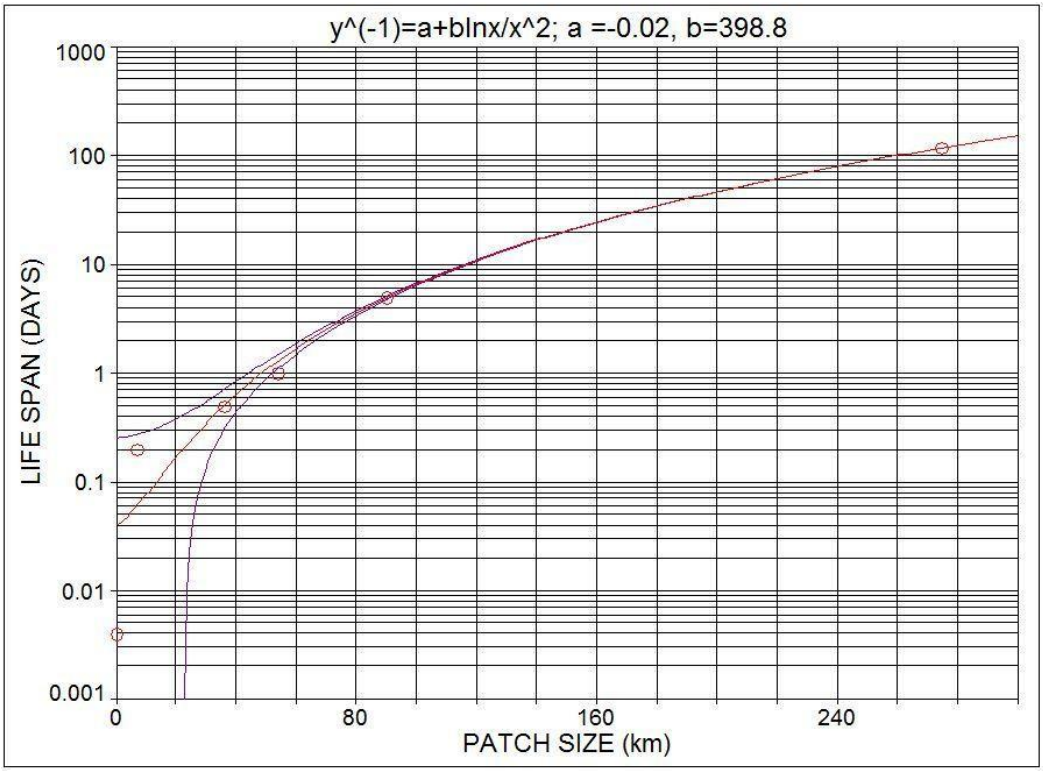

Figure: 8: Time-space relationship of patches (data from Szekielda and McGinnis, 1985)and observations with MODIS in the New York Bight based on repeat observations of patches and the dynamics of Langmuir circulation from repeat aircraft flights over a cyanobacteria bloom (Szekielda *et al.*, 2007). The observations follow the general trend of the equation shown on top of the graph.

The given description of time-space scales is rather restrictive because other factors, such as vertical turbulent mixing by internal waves may not follow this time-space relationship due to their vertical and horizontal scales of tens of meters but hours of propagation. Gradients as observed in blooms, are in many cases extreme and it is assumed that the vertical stability of a patch is also related to its size and survival time. Therefore, such approach to describe the time-space relationship of patches gives a general estimate, although the importance of equilibrium between the physical conditions and the nutrient pool, for example, would still have to be considered separately.

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