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HARMFUL ALGAL BLOOMS IN RELATION TO WIND INDUCED COASTAL UPWELLING AND RIVER PLUMES

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ABSTRACT

Most of harmful algal blooms are produced by dinoflagellates. In coastal upwelling areas, diatoms are usually associated with active upwelling, while during relaxations or reversals, dinoflagellates replace diatoms. Presumably, this change is not only caused by the change in nutrients and turbulence, but also by the influence of river plumes that during upwelling relaxations flow along the coast. In typical coastal upwelling areas, rivers are not common as they are usually associated with deserts (e.g. Sahara, Atacama, Nevada, Kalahari). Nevertheless, in the Iberian Atlantic coast, both coastal upwelling and river discharges are important. The alongshore transport of initial population for developing a dinoflagellate bloom is considered important in upwelling systems. The concept of optimal environmental window is applied to dinoflagellate blooms in upwelling areas. As wind induced upwelling may increase due to the "greenhouse effect", dinoflagellate blooms related to upwelling are expected to change their incidence.

INTRODUCTION

Most harmful algal blooms are caused by autotrophic dinoflagellates, or other organisms with similar characteristics: autotrophy and capacity of perform active vertical displacements. Some diatoms may cause harmful blooms due to their capacity to produce phycotoxins that can be transferred through the marine food web and cause human poisonings. This is the case of the pennate diatom *Nitzschia pungens f. multiseries* (Subba Rao, et al, 1988). Other diatoms, like *Chaetoceros convolutum* can cause physical damage to fish cultured in cages that cannot avoid the algae (Taylor, 1993). This paper only deals with those blooms caused by motile autotrophs.

Winds act on the upper layer of the water column. This layer, in which the applied wind stress is absorbed is called the surface Eckman layer and is the part of the water column where turbulent shear stress is non-negligible. (Brink, 1983). When this layer is affected by alongshore winds having the coast at their left, it is moved offshore due to the Coriolis effect (the opposite in the Southern hemisphere) . The water of this upper layer is then replaced by subsurface water, richer in nutrients which rises near the coast. As turbulence is inherent to this phenomenon, diatoms are the phytoplankters best adapted to this situation in which both turbulence and nutrients are associated (Margalef, 1978). This is the cause why most of the phytoplankton studies in relation to upwelling, consider diatoms to be the major component of phytoplankton in that areas. Nevertheless, Blasco (1975; 1977) considered dinoflagellate blooms in upwelling areas also as an important contribution to their primary production and pointed out the high frequency of "red water" events in upwelling regions. Small (1973), as cited in Small and Menzies (1981), even suggested the idea that greater productivity can be achieved during upwelling relaxation than during strong upwelling. Although they don't mention the responsible organisms of that production, they probably are dinoflagellates.

DISCUSSION

Seasonality

Seasonality of upwelling has been described for the North Atlantic by Wooster et al. (1976) based on observations of sea surface temperature and winds obtained from ship's reports. They found in that area three types of upwelling seasonality. In the South, from 12° to 20°N, upwelling exists from January through May, from 20° to 25°N, upwelling is strong throughout the year, and between 25° and 43°N from June through October. This seasonality is also well expressed by the annual evolution of the upwelling index in these regions (Bakun, 1973). As a consequence of this upwelling seasonality, we can expect a strong influence in the annual cycle of phytoplankton in the affected areas caused by the differences on turbulence and on the aports of nutrients to the photic zone. Margalef (1978) states that primary production appears simply as a function of the external energy supplied to the system, that in case of upwelling systems is basically in the form of wind.

In those upwelling areas where dinoflagellate blooms are frequent, we can also expect an upwelling influenced seasonality on the blooms. The Rías Baixas of Galicia, are bays on the west coast of the Iberian Peninsula that are strongly affected by the Iberian coastal wind-driven upwelling that could be considered in some extent as the Northern prolongation of the Sahara system. In these rias, the estuarine circulation makes the upwelled water entering through the bottom and causing a very high primary production. These rias are one of the most productive areas in the world and shellfish culture is a major industry that is jeopardized every year by harmful algal blooms. Here, there are some species that usually bloomed in summer during the upwelling season, while others bloomed as a result of the upwelling relaxation after the summer. In the case of the summer blooms, they are usually more local phenomena, sometimes restricted to small inlets inside the rias. Although upwelling is the main factor driving the hydrography of the rias, these summer blooms does not depend as directly on upwelling as the autumn blooms that usually happen near the mouths of the rías. In the Rías Baixas, autumn blooms have been associated to the upwelling relaxation that happens after the summer, when the area is no longer under the influence of the Açores that produces the upwelling favourable alongshore winds. When the first low pressure announces the end of the summer, winds change from Northerlies (upwelling-favourable) to Southerlies (downwelling-favourable). This change in winds causes the relaxation of the upwelling and the advection of warmer surface water towards de coast, that coincides with dinoflagellate blooms. (Fraga et al., 1988; 1990; 1993).

Similar mechanisms have been described in other parts of the world. In the South African system, Hortsman (1981) reported a bloom of the toxic *Alexandrium catenella* after two weeks of continuing Southerly winds (upwelling fovorable in west coasts of the Southern hemisphere). He also says that blooms of toxic and non-toxic dinoflagellates occur frequently along the west coast of South Africa but only when wind-driven upwelling is inactive for at least a few days. Pitcher et al. (1993) also associated in the same area downwelling periods with warmer temperature and dinoflagellate blooms, and upwelling periods with colder temperature and diatom blooms.

In the Gulf of Maine, Franks and Anderson (1992) showed an association of a bloom of the toxic dinoflagellate *Alexandrium tamarense* with a buoyant current flowing southward parallel to the coast. Upwelling forces this current offshore while downwelling-favourable winds moved this current towards the coast causing toxicity to shellfish in the seashore on a seasonal way.

Alongshore transport

One problem that rises when an algal bloom is studied, is the identification of the seed population. Three origins can be considered: a) "in situ" populations as vegetative residual stages that need much time to increase their concentration; b) benthic resting cysts that may excyst simultaneously leading to a bigger initial population; c) advected populations.

The first case is not probable in a wind induced upwelling as turbulence will disperse the populations. Excystment does not look either probable as if there is not an advection causing a convergence the recently excysted cells should be also dispersed. The rapid appearance of blooms in upwelling regions could only be explained by advection of a disperse initial population to centers of convergent flow that at least occasionally are the upwelling fronts (Brink, 1983).

The near coast alongshore transport of water in upwelling systems is well known.

Evidences exist also that alongshore poleward offshore currents are over the slope of the continental shelf. Frouin et al. (1990) reported a warm and salty poleward surface current off the coasts of Spain and Portugal. Haynes and Barton (1990) studied this current in September 1986 at the time of an intense *G. catenatum* bloom in the Galician Rias. They found a poleward offshore current that advected towards the north higher salinity water 70 km in only tree days during an upwelling relaxation. When upwelling is strong, this poleward current still flow on deeper waters. According to a numerical model (Batteen et al., 1992) a band of steady equatorward winds which are uniform alongshore but with an anticyclonic wind stress curl results in a equatorward coastal surface current nearshore and a poleward surface current offshore, developing eddies.

Signs of an alongshore transport of initial populations for an algal bloom in Galicia were reported by Estrada et al (1984) when *G. catenatum* and two species of *Prorocentrum* that were not previously recorded in the area were observed south of Lisbon, and a month later they bloomed in Galicia. Moita (1993) also suggests a transport like this in 1985 when *G. catenatum* was observed in August in Cape Roca and bloomed off the north of Portugal and off Galicia in November. An alongshore transport of cells to develop a bloom was also suggested by Blasco (1977) to explain a bloom of *Gonyaulax polyedra* in the upwelling region of Baja California, based on the parallelism in the distribution of dinoflagellates and low salinity water. Franks and Anderson (1992) also suggested a transport of *Alexandrium tamarense* along the coast of the Gulf of Maine.

During a recent cruise off the coast of Galicia and Northern Portugal, a bloom of the toxic dinoflagellate *G. catenatum* was observed centered over the shelf-break off Figueira da Foz (unpublished data) at the same time that no toxicity was detected on shellfish near the coast (M.A. Sampayo, personal communication). Approximately ten days later, this species was detected in the plankton of the Galician rias, around 200 km to the North, causing toxicity to mussels.

The alongshore poleward transport of water during upwelling relaxations is even considered by Send et al. (1987) as more important for the coastal warming than the offshore-inshore advection.

River plumes

The most important coastal upwelling regions in the world are those in the eastern boundaries of the Oceans, like the western coast of USA, Southamerica, Western Sahara or Namibia due to the important alongshore equatorward winds. The relative cooling of the surface water of these regions compared to the offshore water at the same latitude causes the air to dry, and then deserts are common on the continents near the coasts of the upwelling areas, like Nevada, Atacama, Sahara and Kalahari deserts. River discharges are then very unusual in upwelling systems. Nevertheless, there are some cases in which river exists, like Columbia River in the Northwest coast of USA, or like Tagus, Duero or Miño rivers in the west coast of the Iberian peninsula.

The Columbia River plume has been well studied. Huyer (1977) pointed out the importance that Columbia river plume has in the salinity over the continental shelf off Oregon and Washington. During winter, winds are poleward and the surface currents are northward and towards the coast. When the Columbia River water enters the shelf, turns to the right due to the Coriolis effect and flows along the coast of Washington. In summer, with opposite winds upwelling-favourable, the plume lies southward and offshore the Oregon coast. Fiedler and Laurs (1990) studied the variability of the Columbia River plume with the aid of satellite imagery and found that it is easier to follow its evolution with images of Coastal Zone Colour Scanner (CZCS) which reflects both sediments and phytoplankton pigments. With an appropriate pigment algorithm their pictures show dramatically the strong influence of the river plume variability, according to winds, on the distribution of the phytoplankton biomass in the region. Small and Menzies (1981) stated that the Columbia River plume, close to the coast during upwelling relaxation compress the biomass towards the shore. This fact was also observed by Fiedler and Laurs (1990) who suggest that during wind reversals, even if they are very weak and brief, the plume moves to the North with the Corioli deflection, much more readily than to the South. During upwelling events, when the river plume flows southward parallel to the coast, if it is not too far from it, its inshore boundary coincides with the offshore boundary of the upwelled water, the upwelling front. There are some evidences that the front may not have a very strong kinematic effect during active upwelling, while during relaxation, the front appears to have a dramatic effect on the near-surface flow field (Brink, 1983). Small and Menzies (1981) found the evidence that relatively high biomass can move into the shore under strong, rapid wind reversals to upwelling-unfavourable winds, occurring these changes in biomass distributions quickly. This is an important fact that can explain the sudden appearance of dinoflagellate blooms on the shore.

Unfortunately, the plumes of the rivers of the West coast of the Iberian Peninsula have not been so intensely studied, but similar features as those of the Columbia River plume can be observed in satellite pictures. Mouriño and Fraga (1982) reported that in the mouth of the Ría de Vigo, the salinity decreased after Southerly winds, not due to the fresh water discharge on the ría, but to the River Miño plume pushed towards the North and the coast in a similar way to the Columbia River plume in the coast of Washington. Fraga et al. (1993) have associated a bloom of *G. catenatum* in Ría de Vigo in 1990 with a reversal of the upwelling-favourable winds that moved warm offshore water towards the coast where apparently it lowered its salinity by mixing with the river discharge. When the Columbia River plume flows towards north, it is probably a mixture with oceanic surface water driven onshore. (Fiedler and Laurs, 1990). Moita (1993) described the evolution of a bloom of *G. catenatum* off Porto that looks associated with the Duero River plume whose mouth at the North, is not very far from the studied transect.

Fig. 1 shows a conceptual diagram of the evolution and interaction of River Miño plume with the upwelled water, the outflow of heated water of Rias baixas and offshore warm surface water. At the end of the summer, when upwelling is still active, these four bodies of water are more or less apart moving towards the South and offshore, except the warm offshore water beyond the upwelling front. When winds reverse to Southerlies, the river plume flows toward the north along the coast until it finds the warm outflow of the Ría de Vigo. At the same time the warm offshore water moves inshore covering the upwelled until the three lighter bodies of water meet forming strong gradients and mixed laterally.

Optimal environmental window

In wind induced coastal upwellings, (Eckman-type) the intensity of upwelling is proportional to the wind stress, so it will be also proportional to the turbulence. Cury and Roy (1989) introduced the concept of the "optimal environmental window" to explain the relation between recruitment variability of pelagic-spawned fish and upwelling indices. They found that this relation is dome shaped. There are two different limiting factors that affect recruitment. At weak upwelling intensity the lack of nutrients in the photic zone limits the production of food for the larvae, and at strong upwelling, the strong turbulence has a negative effect on the survival of the larvae. This idea can be applied also to dinoflagellate blooms. Eppley et al (1968) and Eppley and Harrison (1975) related dinoflagellates with weak upwelling, so the nutrient rich water did not reach the surface. In Ría de Vigo, in 1986 a big bloom of *Gymnodinium catenatum* took place. The bloom started when summer upwelling relaxed, and warm offshore water was advected towards the coast. Once an initial population was established by advection, a very short upwelling event injected cold and nutrient rich water in the Ría through the bottom. This water did not reach the surface that remained warm, and it was too deep for diatoms, but it was a nutrient source for developing a dinoflagellate bloom. (Fraga et al., 1990). In another study of this same bloom, (Figueiras and Fraga, 1990; Fraga et al, 1992) the transport of nutrients from lower to higher layers by vertical migration of *G. catenatum* was demonstrated based on the variations of the parameters 'NO', 'PO' and 'CO' proposed by Broecker (1974) that are characteristic constants of each type of water. In this case their variations can only be explained if *G. catenatum* uptakes nutrients at depth and photosynthesizes near surface. If the short upwelling event that brought the nutrients to a depth accessible for only vertical migrators were stronger, dinoflagellates would be dispersed and replaced by diatoms. Figueiras and Rios (1993) observed that 10m is a critical depth for the nutricline. If upwelling is intense it will rise and provoke diatom growth, and if upwelling is too weak, the nutricline will be at a depth where the organisms are unable to reach. We may apply the optimal environmental window concept to dinoflagellate blooms with the aid of the Margalef's phytoplankton mandala (Margalef et al. 1979) (Fig. 2) .The X axis can be proportional to the intensity of an Eckman-type upwelling in which nutrients and turbulence go together, and represents also the production potential. The Y axis represents a gradient. Following what they call the "main sequence" of phytoplankton, weak winds correspond to phytoplankton communities dominated by flattened dinoflagellates, and as wind increases and hence upwelling, the phytoplankton changes to diatoms. In case of upwelling relaxation phytoplankton will be dominated by dinoflagellates again. The "red tides sequence" appears on the top of the figure at a higher gradients and in an intermediate position over the range of potential production. To go from the "main sequence" to the "red tide sequence" an extra supply of nutrients not related to turbulence is necessary . In wind-driven coastal upwelling ecosystems where river discharges are important, this supply of nutrients could be aported by the freshwater (they could be just humic substances). When the upwelling is strong, the nutrients of the river plume are moved offshore and added to the high turbulence-related nutrients. When upwelling relaxes and the river plume lies along the coast, gradients are bigger and the freshwater nutrients can change phytoplankton succession from the "main sequence" to the "red tide sequence". According to this model, the optimal environmental window should be wider with bigger supplies of extra nutrients not related to turbulence. Then, we can expect more frequent harmful algal blooms in coastal upwelling systems having river plumes, than in those lacking them.

Greenhouse effect

If dinoflagellate blooms in upwelling areas depend on the intensity and timing of the upwelling, any change in these variables will have an effect on the dinoflagellate blooms. One of the effects of the global climatic change is an increase in the temperature difference between continents and oceans due to heating of the land. This difference will increase the alongshore winds favourable for upwelling (Bakun, 1990). The effects of this increase in upwelling intensity on algal blooms occurrences could be opposite in different places. In areas dominated by strong upwelling most of the year, we can expect a decrease in the number of dinoflagellate blooms, as it will be less upwelling relaxations. Nevertheless in other areas were upwelling is more seasonal, an increase in the incidence of dinoflagellate blooms could be expected, as it is the case of the blooms of the toxic dinoflagellate *G. catenatum* in the coast of Galicia (Fraga and Bakun, 1993). Wooster et al. (1976) showed the dependence of upwelling ecosystems on latitude. In tropical areas upwelling is present through the whole year, and with increasing latitude, the upwelling season becomes narrower. An increase in upwelling intensity due to the "greenhouse effect" could extend the upwelling season in the high latitude extremes of upwelling regions with the subsequent effects on algal blooms.

SUMMARY

a) In wind-driven coastal upwelling areas, upwelling relaxation causes warm offshore surface water to collapse to the coast increasing the temperature of inshore waters.

b) This movement of water produces dramatic changes in the phytoplankton, from diatom dominated communities to dinoflagellate dominated ones. This movement may cause coastal blooms in convergence areas.

c) Alongshore advection of phytoplankton seems to be an important factor in seeding dinoflagellate blooms.

d) During upwelling events, river plumes are extended equatorward and displaced from the coast. After upwelling, with downwelling-favourable winds, river plumes lie along the coast, flowing poleward. When this happens, the freshwater runoff may favor the growth of dinoflagellates due to the aport of humic substances and to the increasing gradients.

e) The concept of optimal environmental window developed for understanding pelagic fish recruitment, can be applied also to dinoflagellate blooms.

f) As it is expected the upwelling systems to be affected by the global climate change, those harmful algal blooms related to upwelling are subjected to change their incidence.

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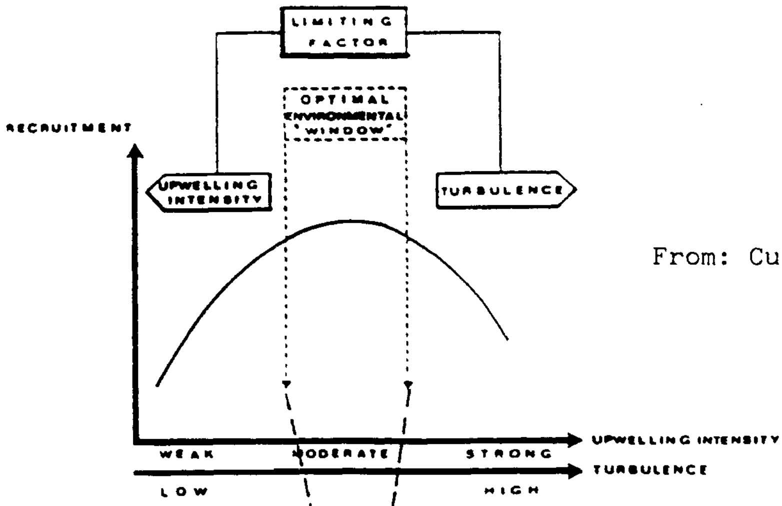
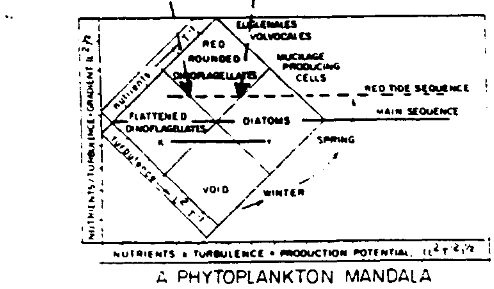


From: Cury and Roy, 1989



From: Margalef et al., 1979

FIG. 1. Optimal environmental Window and Phytoplankton mandala

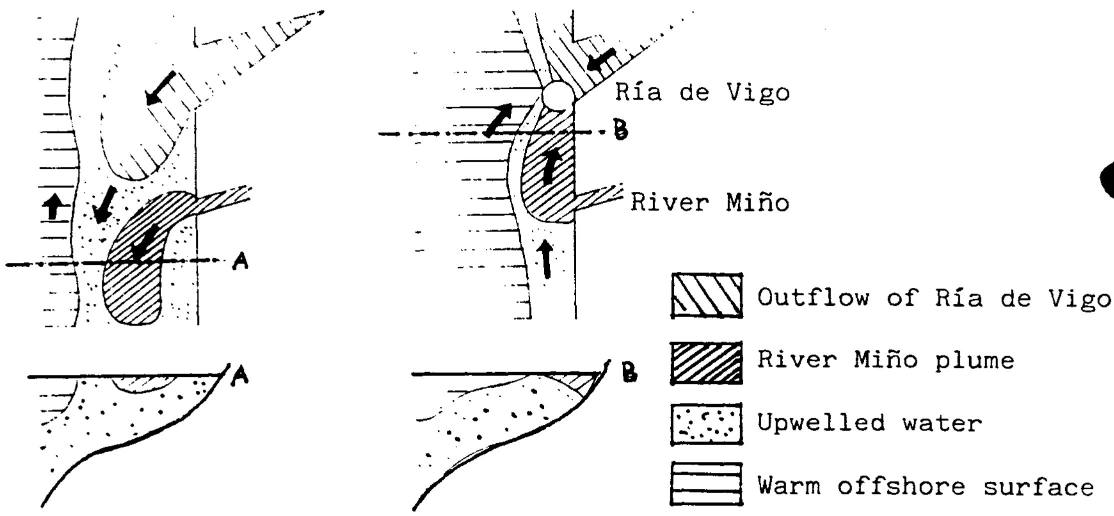


FIG. 2. Conceptual diagramme of the interaction of different water bodies on the shelf off Ría de Vigo and River Miño, during upwelling (A),and after an upwelling relaxation