Toxic Phytoplankton Blooms in the Sea
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GLOBAL CLIMATE CHANGE AND HARMFUL ALGAL BLOOMS: THE EXAMPLE OF *Gymnodinium catenatum* ON THE GALICIAN COAST

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ABSTRACT

A scenario is presented in which the incidence of blooms of the toxic dinoflagellate *Gymnodinium catenatum* on the coast of Galicia (NW Spain) could increase due to global climate change. Blooms of *G. catenatum* in the Galician rias appear to be related to the autumn relaxation of upwelling. This results in the incursion of warm, nutrient-depleted surface water into the rias, deepening the nutricline. Being a chain-former, *G. catenatum* is an effective swimmer and better adapted to vertical migration than other dinoflagellates. Thus, a deepening of the nutricline may favor this species which is capable of migrating to the deep layers to take up nutrients. It is expected that atmospheric "greenhouse" effects will intensify equatorward wind stress along the west coast of the Iberian Peninsula during spring and summer, thereby amplifying coastal upwelling. This would increase the temperature difference between recently upwelled waters and surface waters of oceanic origin, and enhance primary production and mussel growth within the rias during summer. The estuarine circulation of the rias would then export increased particulate organic matter (phytoplankton and mussel feces) from the rias. This organic matter would tend to settle and remineralize on the continental shelf near the mouth of the rias, increasing the nutrient concentration of the waters entering the rias below the nutricline. The combination, during fall, of increased nutrient concentrations below a deepened nutricline and a more strongly stratified water column would seem to be particularly favorable to *G. catenatum*. The first recorded observation of this species was in 1976 when the first PSP outbreak associated with Galician bivalves was also reported. Conversely, *Gonyaulax polyedra,* a common bloom species in the past, is now rare in the rias.

INTRODUCTION

Recent decades have seen a continuing build-up of CO_2, methane, chlorofluorocarbons, and other greenhouse gases in the earth's atmosphere. The scientific consensus is that substantial global warming and other important climatic effects are likely [1]. There is growing concern that associated changes in the coupled atmosphere-ocean system, brought about by this accumulation, may have major effects on marine ecosystems, their living resources and associated human cultural and economic values. One "greenhouse effect" which seems certain is an increase in temperature contrast between the heated continental land masses and the oceans during the warmer seasons of the year. This would lead to amplified sea breeze circulations and alongshore coastal winds, correspondingly enhanced offshore Ekman transport in the ocean surface layer, and intensified coastal upwelling [2].

Another important global trend related to human activities is the increased economic and public health problems related to harmful algal bloom phenomena [3]. Although these trends have not been linked mechanistically, the potential for linkage of global climate change to the harmful bloom problem is certainly of great interest.

The ocean adjacent to the west coast of the Iberian Peninsula is a "classic" eastern ocean coastal upwelling system. The upwelling process is highly seasonal, being most intense in spring and summer, but relaxing during fall and winter [4]. Nutrient-rich, upwelled waters provide a basis for high rates of organic production, a rich trophic pyramid and important local fisheries. Major mariculture operations occur in the Rias Bajas, a series of oceanic bays on the coast of Galicia (Fig. 1), where intermittent enrichment during upwelling events supports intensive raft culture of mussels [5]. The toxic dinoflagellate *Gymnodinium catenatum* Graham was first observed in October, 1976, coinciding with the first recorded outbreak of paralytic shellfish poisoning (PSP) in Spain [6]. Over the past decade, PSP outbreaks have become a serious threat to the local mariculture industry.

This paper utilizes recent advances in understanding the ecology of chain-forming dinoflagellates, such as *G. catenatum*, and the likely effects of global climate change on coastal upwelling ecosystems, such as the Galician Coast, to provide an example of a credible scenario for linkage of global climate change and harmful algal bloom phenomena. The goal is to stimulate discussion and motivate interdisciplinary research activity on a topic of potentially serious socio-economic and public health concern.

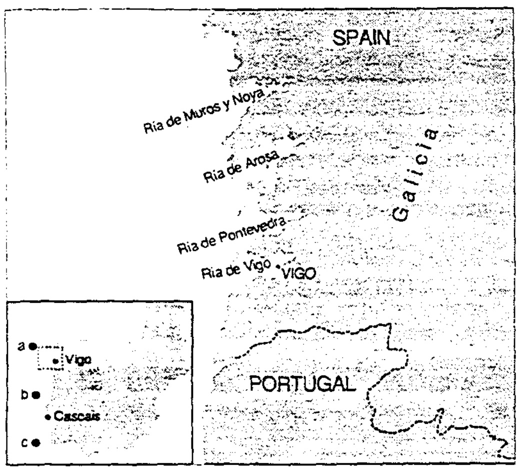

FIG. 1: The Iberian Peninsula, with locations referred to in text and detail of the Rias Bajas region.

CLIMATE CHANGE AND UPWELLING ECOSYSTEMS

Eastern ocean upwelling ecosystems are the most productive, extensive ocean areas of the world. In such regions, equatorward alongshore winds cause offshore transport in the surface Ekman layer. This loss of surface water near the coast is balanced by upwelling of cool, nutrient-rich waters from depth. During active upwelling, the offshore surface Ekman flux maintains a slight sea surface slope implied by the density difference between the upwelled water near the coast and the lighter surface waters a short distance offshore. However, during relaxations or reversals in upwelling-producing wind stress, the lighter oceanic surface water tends to collapse coastward [7], overrides the newly upwelled water, and downwells at the coast. Downwelling has been observed to extend to within the Rias Bajas, following the initial seasonal relaxation of upwelling along the Galician coast [8].

The vigorous alongshore wind that drives the upwelling is supported in part by a strong atmospheric pressure gradient between a thermal low pressure cell that develops over the heated land mass and the higher barometric pressure offshore over the cooler ocean. This is one reason why upwelling seasons tend to encompass nearly the entire year in tropical eastern ocean boundary systems but, with increasing latitude are more restricted to a late spring to summer period [4]. Greenhouse-related amplification of heating during spring and summer would intensify the thermal low pressure cell, enhancing the onshore-offshore pressure gradient. The stronger pressure gradient would strengthen the alongshore geostrophic wind, causing enhanced offshore Ekman transport and amplified coastal upwelling. The increased upwelling and mixing implied by such a wind increase, by cooling the coastal ocean surface layers and further accentuating the ocean-continent temperature contrast, might constitute a positive feedback loop [2] further amplifying the effect.

Eastern sides of oceans have a much drier atmosphere than western sides. Since the most important greenhouse gas in the atmosphere is water vapor, the global accumulation of CO_2, methane, chlorofluorocarbons, etc., will have a larger relative greenhouse effect along eastern ocean boundaries than in other ocean regions. Thus, one would expect the effect to emerge from the "noise level" of natural, short term climatic variability earlier in these regions than elsewhere. However, since the effect on the wind system is to increase upwelling and mixing (both of which cool the sea surface), it is not surprising that general increases in average sea surface temperature have not been an evident consequence in these systems. On the other hand, the intensity of upwelling-producing wind stress (Fig. 2) off the Iberian Peninsula has appeared to increase dramatically during spring and summer over the past four decades [2, 9, 10]. During this period, a sustained increase in spring-summer alongshore sea level slope (relative to fall-winter) (Fig. 2d) tends to corroborate this trend. These and various other aspects of the seasonality and geography of wind stress trends throughout the North Atlantic conform well to a greenhouse effects scenario [10].

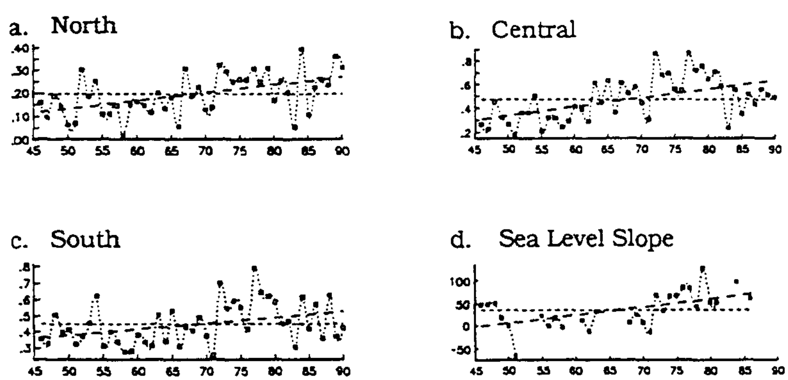

FIG. 2: Long term (1946-1990), increasing trends in upwelling-producing wind stress and alongshore sea level slope (after [10]). Panels a, b, c: spring-summer (April to September) average monthly wind stress (dyne cm^{-2}) for three locations (a, b, c) off the Iberian coast (see FIG. 1). Long-term mean for each series indicated by horizontal, dashed line. Linear trend lines fitted by least squares. Panel d: seasonal (spring-summer minus fall-winter) difference in sea level slope (in mm) between Cascais and (minus) Vigo (see FIG. 1).

ECOLOGY OF *Gymnodinium catenatum* IN THE RIAS BAJAS

In a study of nutrient dynamics within the rias, Fraga [11] provided the scenario diagrammed in Figure 3: "In spring the upper levels of the NACW (North Atlantic Central Water) rise above the level of the bottom of the Rias, and nutrient-rich water reaches the photosynthetic layer inside the rias leading to high primary production. Part of the biomass produced is transported in the surface layer towards the mouth of the rias, sinks to the bottom, and decomposes. This enriches the deep water, which flows back into the rias." A relationship exists between mussel production within the rias and intensity of coastal upwelling outside the rias [12], based on a comparison of a mussel-condition index (% solids) and an upwelling index [13] computed from the atmospheric pressure gradient at a point 150 km off Cape Finisterre. Thus, the amount of particulate solids involved in the transport, sinking, decomposition, and remineralization loop (Fig. 3) would tend to increase with upwelling intensity.

G. catenatum blooms in the Galician Rias have been associated with the autumn relaxation of the summer upwelling [14, 15]. In late summer, sea surface temperatures in the rias are relatively cool due to the influence of coastal upwelling. Offshore, warm and salty water related to a coastal current [16] occurs at the surface. When the prevailing southward winds, which drive summer upwelling, relax or turn northward in the fall, the surface waters held offshore by the wind-induced offshore Ekman flux collapse toward the coast causing downwelling in the rias. Phytoplankton dominance then changes from diatoms to dinoflagellates. *G. catenatum* is one of the dinoflagellate species that may bloom at this time (see Fig. 2 in [17]). When this occurs, mussels may become toxic to humans [14].

Vertical migration is an important factor in dinoflagellate blooms. *G. catenatum*, as observed during a bloom in the Ria de Vigo in 1986 [8], is able to undertake daily vertical migrations to transport nutrients from the deep nutricline to the illuminated surface layers for use in photosynthesis. In Galicia, *G. catenatum* commonly blooms together with *Alexandrium affine* in areas of downwelling, inside or near the mouths of the rias. These two species and other "red tide" dinoflagellate species can form long chains. Fraga *et al.* [18] reported that the swimming speed increases with chain length. This apparent hydrodynamical advantage results in the chain-forming dinoflagellates being better adapted for vertical migration than single-celled forms. (We diagram this "fall" scenario in Fig. 4). The advantage may be substantial when significant downwelling is occurring and/or the nutricline is deep. Thus, the depth of the nutricline appears to be a selection factor for chain-forming species over single-celled dinoflagellates or non-motile phytoplankters such as diatoms.

A SCENARIO LINKING CLIMATE CHANGE TO TOXIC BLOOMS

The following "linkage scenario" is accordingly proposed. If climate change leads to increased upwelling intensity, the input of nutrients and primary production in the rias will increase during the upwelling season (April - September). The production of particulate organic matter, notably increased fecal matter from increasingly well-nourished mussel culture, will also increase and enter the transport, sinking, decomposition, and remineralization "loop" (Fig. 3). This would result in a greater accumulation of decaying organic matter on the bottom. Subsequent remineralization would increase nutrient concentrations in the layer beneath the deep nutricline following the upwelling season (Fig. 4). Vertically-migrating, chain-forming phytoplankters, such as *G. catenatum*, would have the best access to this increased deep nutrient pool.

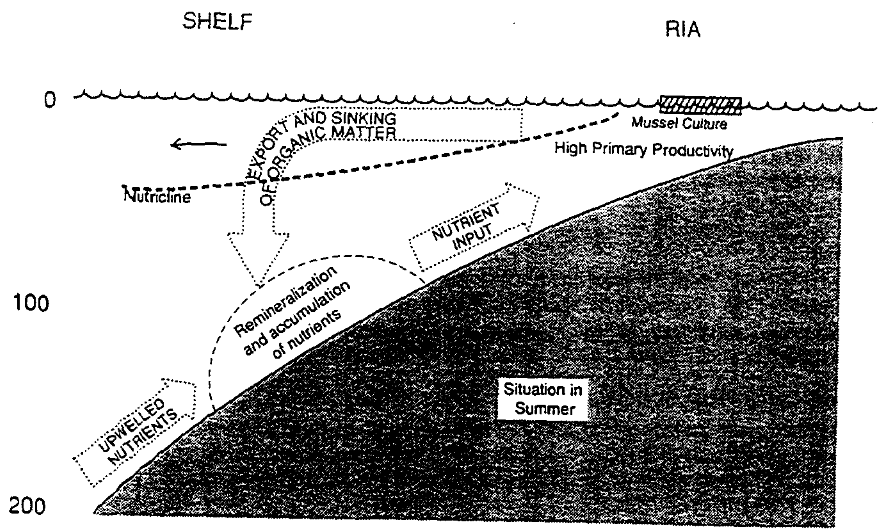

FIG. 3: Diagram of summer nutrient dynamics in the rias and adjacent continental shelf illustrating the "loop" consisting of upwelling-enriched primary production, which leads to export, sinking, and bottom accumulation of particulate organic matter, which decays, remineralizes, and enriches waters beneath the nutricline which may be resupplied to the photic zone by subsequent upwelling.

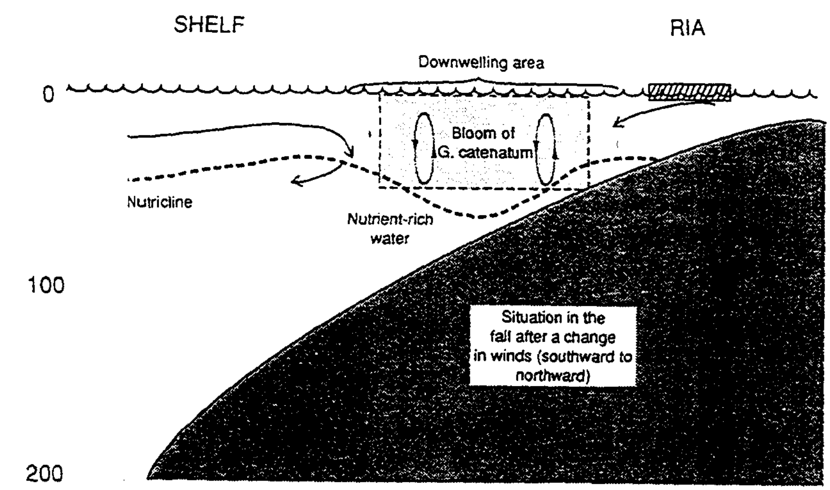

FIG. 4: Diagram of nutrient dynamics after fall relaxation of upwelling. Lighter oceanic surface waters collapse toward the coast producing a downwelling zone in the rias which cuts off upwelled enrichment of the photic zone and depresses the nutricline. Vertically-migrating dinoflagellates may access the nutrient pool beneath the nutricline and transport assimilated nutrients to the photic zone for use in photosynthesis.

In addition, an increased upwelling intensity would be expected to increase the equatorward sea surface slope along the Iberian Peninsula. Thus, the initial collapse of the offshore surface water towards the coast upon cessation of the upwelling wind would tend to be intensified. (An increased southward, alongshore sea surface slope would increase the tendency for coastward geostrophic flow and tend to break down (by opposing southward momentum) maintenance of the offshore sea surface slope by Coriolis force, which holds the lighter oceanic surface waters offshore). This would enhance the episodic, fall downwelling within the rias and deepen the nutricline, favoring forms such as *G. catenatum* which are adapted for vertical migration.

As noted above, there is evidence that both upwelling intensity and seasonal (upwelling vs. non-upwelling) differences in sea level slope are indeed increasing along the Iberian coast and in other eastern ocean boundary regions. An apparent change in bloom species has also been observed [19] in the Rias Bajas. The first known reports of "red tides" in Galicia are from 1916 and 1917 [20], with the next report from 1955 [21]. In these three earlier blooms, *Gonyaulax polyedra* was the main species, but is now rare in these waters. In fact, several species which now form "red tides" in the rias (*G. catenatum, A. affine, Prorocentrum triestinum, Heterosigma akashiwo*) were not reported before the last decade. The hypothesis that these species represent recent introductions has been popular, given the introduction of viable dinoflagellate resting cysts into Tasmanian waters from the ballast waters of large cargo ships [22]. Admittedly, climate change is not the only potential explanation. The environment within the rias has been subjected to substantial alterations within this century. The human population inhabiting the shores of the rias has increased dramatically and mussel culture, initiated in the 1950s, has substantially altered nutrient dynamics in the rias.

Although aspects of this proposed scenario linking toxic bloom phenomena to global climate change are speculative, it represents a logical sequence of reasonably likely circumstances. The possibility emerges that an affect on harmful algal bloom phenomena may be one of the most direct consequences of climate change with regard to impacts on marine ecosystems and associated human values. There presently seems to be a nearly total absence of focus on this problem area within the various national or international global climate change research programs. It would, therefore, seem prudent to seek ways to encourage the design and implementation of expanded research activities in this area.

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