

Numerical simulations of *Emiliana huxleyi* blooms and modelling coccolith calcite production in the North Atlantic.

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A simple, one-dimensional mixed-layer model has been created, which calculates blooms and annual rates of production of organic and inorganic carbon by the coccolithophore *Emiliana huxleyi* at various latitudes and during different seasons in the Eastern North Atlantic.

In the model the watercolumn is subdivided into three layers, a seasonally and latitudinally varying mixed layer at the surface, a thermocline layer below with constant thickness and a "bottom layer" of infinite depth, which represents the deeper part of the ocean. Temperature varies with season.

The light intensity varies also with season and latitude and includes a daily light-dark cycle with seasonally and latitudinally varying durations of the illumination period. Of the 38% photosynthetically available radiation (PAR, 400nm-700nm) within the spectrum of solar radiation about 53% is globally attenuated within the atmosphere (reflection, scattering and absorption as a function of latitude) and another fraction is reflected at the air-water interface, the sea-surface albedo also varying with season and latitude.

The water entering solar radiation is split into three equally wide wave-bands of red, green and blue light, each band obeying the exponential decay function as is described by the law Lambert-Beer, but with different extinction coefficients. The extinction coefficients depend on the concentrations of suspended chlorophyll, coccoliths and coccospheres, and from these the depth of the euphotic zone is calculated.

Two phytoplankton groups, coccolithophorids and diatoms are included to mimic nutrient competition. Both groups reproduce in the mixed and thermocline layers by cell division. Cells within each phytoplankton species are identical in size and populations have no age structure. In the bottom layer no photosynthesis is possible any more and it is assumed, that phytoplankton concentrations are negligibly small and are kept at low and constant levels. Nutrients are dissolved nitrate and silicate. A simple nutrient model, which is based on field data from APNAP II and JGOFS expeditions, was included to simulate latitudinal variations of silicate and nitrate at depths greater than 100m.

Growth of both phytoplankton groups is determined by ambient light, temperature and nitrate concentrations, and for diatoms silicate concentrations as well. Calcification in coccolithophorids is coupled to the specific growth rate and is modulated by the light intensity. Although in reality coccolithophorid biomass and attached liths form a single particle, they are treated as two separate components. Both, however, sink and mix simultaneously in and between the different vertical compartments. Coccolithophorids detach parts of their coccolith cover into the water as has often been observed in natural blooms of *Emiliana huxleyi*, and which renders bloom waters a milky turquoise colour. Physiological processes leading to coccolith detachment, however, are still very poorly understood. Therefore, the rate of coccolith detachment is tentatively modeled as a function of the number of attached liths per cell, as was suggested by the few published culture experiments. The vertically integrated annual production of organic carbon and coccolith calcite (in grams C or calcite $\text{m}^{-2} \text{yr}^{-1}$) were calculated from the specific growth rates, per cell calcification and the depth of the euphotic zone.

All suspended particles and dissolved nutrients are assumed to be homogeneously distributed in each layer. The exchange of phytoplankton cells, free and attached liths and nutrients between the mixed and thermocline layers, and the thermocline and bottom layers obeys turbulent mixing, which is formulated as a linear function of the gradient of the respective components between two adjacent layers, the intensity of which is controlled by turbulent mixing coefficients. Living cells of coccolithophorids and diatoms sink through the watercolumn at constant settling rates, while free liths, which are very small, remain in suspension. Grazing of coccolithophorids and diatoms by zooplankton are treated as a loss term, without explicit calculation of a grazing population. These loss terms are calculated as the products of the coccolithophorid or diatom densities times a seasonally varying intrinsic grazing rate. Grazing includes the ingestion of attached liths on a coccosphere and the ingestion of free liths, which mimics sloppy feeding. A set of 12 linear differential equations describe this ecosystem and was numerically solved by means of the finite difference approximation. Programming language was Fortran 77 and model runs were done on a Macintosh Quadra 800.

Preliminary results.

The model reproduces the correct succession of diatom and *E. huxleyi* blooms. Bloom formation is triggered by the combination of a shoaling mixed layer, the increasing illumination, rising temperatures, low to moderate grazing pressure and high nutrient levels within the euphotic zone. The main limiting factor for the size and duration of the modeled diatom blooms is the amount of available silica in the mixed layer. The time of onset and the magnitude of *E. huxleyi* blooms are mainly determined by the amount of dissolved nitrate, which is left over after the end of the preceding diatom bloom and the grazing pressure. The maximum concentration of detached coccoliths in the water occurs after the period of maximum cell growth of *E. huxleyi*. This situation is very similar to natural blooms, where satellite imagery and direct ship observations from the North Atlantic and adjacent shelf areas have shown, that the highest reflectivity in surface waters, which is caused by abundant detached coccoliths, is indicative for the latest phase of an *E. huxleyi* bloom. At low latitudes, where all other conditions phytoplankton growth are favorable, the persistent shortage in nutrients prevents the formation of blooms.

Although working at low to mid-latitudes, the model still fails to explain *E. huxleyi* blooms at high latitudes. At 60°N for example, the predicted concentration in chlorophyll a for *E. huxleyi* is only 0.25 mg m⁻³, whereas maximum chlorophyll concentrations during an extensive bloom of this species in the South Iceland Basin in 1991 have been of the order of 2 mg Chla m⁻³. The reasons for this behaviour of the model is not yet clarified. Possible causes could be a too deep mixed layer during late spring/early summer. Monthly averaged seasonal and latitudinal variations of the mixed layer depths in the North Atlantic were parametrized from an oceanographic Atlas indicating 30m as minimum values during summer. More recent shipboard measurements during an *E. huxleyi* bloom, suggest, that the mixed layer thickness during an *E. huxleyi* bloom may be as low as 20m also at high latitudes, which could at least partly be a reason for the difficulties. However, of all the reasons, that were taken into consideration, none was sufficiently strong to explain the failure to simulate *E. huxleyi* blooms at high latitudes. This may illustrate, that we eventually have to look out for other, hitherto unknown factors to explain the natural occurrence of *E. huxleyi* blooms at high latitudes, such as the Iceland Basin, the Shetland Islands or the Greenland Sea), or that we have to modify the layer structure of the model (change to a vertically continuous model).

Another problem, which has not yet been fully solved is the annual production of organic and inorganic carbon. Multi-year simulation runs have shown, that even after attaining steady state conditions, annual and vertically integrated production rates of organic and inorganic carbon are much too high when compared with field data. More realistic sub-models for growth and calcite production in *E. huxleyi* on cellular level under nutrient and light saturated conditions but with varying temperatures have to be developed for this purpose. Also a more realistic model to describe the underwater light-field and spectral characteristics for algal growth and calcification have to be implemented.