HARMFUL ALGAL BLOOMS IN THE OCEAN: AN EXAMPLE TO INTRODUCE HIGH SCHOOL STUDENTS TO ENVIRONMENTAL PROBLEMS

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ABSTRACT

Tackling problems in environmental science needs an interdisciplinary approach in which physics, chemistry and biology are coupled to address the impact of global change on processes in atmosphere, oceans and biosphere. Using simple conceptual models of populations we demonstrate (i) the complexity of the dynamics which can arise due to changes in the environment and (ii) how to analyze the problem of the formation of harmful algal blooms in the ocean. Furthermore, we show how methods from theoretical physics can be utilized to model ecological processes.

INTRODUCTION

School education is mostly devoted to the different science subjects like physics, chemistry and biology taught independently of each other. However, most major problems in climate and environmental science require the intimate interplay between different disciplines to understand e.g. the impact of changes in the physical environment like global warming on ecosystems. For this reason it would be most appreciated if already at the school level one would start demonstrating with simple models how important questions in environmental science can be tackled combining different disciplines of science. Here we will give a short introduction into some phenomena in ecosystem dynamics, particularly in marine science. We use methods borrowed from physics to set up the model and to analyse it. Furthermore we show how the physical environment influences the dynamics of the biological system.

Phytoplankton are organisms living in all oceans, rivers and lakes and can be considered as plants since they produce organic material from inorganic nutrients utilizing sunlight for photosynthesis. Moreover, phytoplankton constitutes the base of the aquatic food web [1] and produces more than half of the oxygen in the world [2]. Furthermore, it is an integral part of the global carbon cycle [3] and plays, hence, a major role in climate dynamics. Changes in phytoplankton dynamics would thus have major consequences for mankind. Due to seasonal changes in temperature and light conditions, i.e. the physical conditions in the environment, phytoplankton species develop large abundances called algal blooms mostly in spring and some also in the autumn. Such blooms, in turn, trigger the growth of species at higher trophic levels like zooplankton and fish, which feed upon phytoplankton. The phenomena, which we would like to address here specifically, are so-called harmful algal blooms that are caused by species, which are e.g. capable of producing harmful substances supressing the growth of competitors and predators or even leading to their death due to the toxicity of those substances. Besides the toxic substances can accumulate in predators and finally be transferred to organisms on higher trophic levels like fish and humans. Therefore, harmful algal blooms may cause large economic losses due to their threat to fish farming and the health of people. Moreover they have a severe impact on ecosystem dynamics.

To gain some insight into the formation of harmful algal blooms, we will firstly discuss briefly the main steps of modelling in science with particular emphasis on models in ecology. This methodology is based on the theory of nonlinear dynamical systems. Next, we will demonstrate that even in rather simple population models the dynamics can be rather complex and discuss the limits of predictability. Finally we analyse a particular model of harmful algal blooms to illustrate how changes in the environment influence the emergence of harmful algal blooms. Using these simple illustrations one can get school students interested in modelling environmental problems.

MODELLING ECOLOGICAL DYNAMICS

Dynamical systems are frequently used to study various phenomena from diverse disciplines of science such as laser physics, population ecology, socioeconomic studies, and many others. The corresponding mathematical models are often formulated in terms of balance equations, in which the time evolution of the state variables is determined by possibly several gain and loss terms. In the modeling process the modeler usually decides first which processes are important and need to be included in the model and second, which specific mathematical function describes best those processes and reflects either empirical evidence or some theoretical reasoning. In this way a specific model for the phenomenon under consideration is constructed.

When constructing models in physics one begins usually from the first principles like e.g. Newton’s laws in mechanics. However, in ecology such first principles are not available and the modeler has to formulate mathematical functions for processes like growth, competition, predator-prey interactions like grazing or death. In literature several such formulations are provided which fulfill some basic biological features. To illustrate the obtained dynamics we discuss here the formulation of growth as well as predator-prey dynamics.

In the simplest form the growth of a species X is modeled using a constant growth rate *r* of an individual which is multiplied by its abundance leading to an overall growth term $dX/dt=rX$. This formulation would lead to an exponential growth $X(t)=X(0)exp(rt)$, which is rather unrealistic since it does not take into account, that resources as a necessary input for growth are in general limited and individuals will compete for these resources. If one also considers this limitation, then one has to include a term for the competition, which can be expressed as a quadratic term in the abundances of the species *X*. This formulation results in a differential equation containing one gain term, the growth, and one loss term, the competition for the constant resource *K*, called carrying capacity:

$$\frac{\mathrm{dX}}{dt} = rX\left(1 - \frac{\mathrm{X}}{K}\right) \qquad (1)$$

The dynamics of this limited growth leads to a constant equilibrium in which the gain balances the losses resulting in an abundance of the species, which equals the carrying capacity. A growth described in this form is called logistic growth [4].

This situation changes if the model does not describe a system in which the time is continuous, but discrete [5]. Such population models represent species, which have a yearly breeding cycle like insects and birds and in which the number of individuals is counted each year at approximately the same time. The corresponding dynamics can be expressed in terms of a map in which the index i denotes the year in which the population is considered:

$$X_{i+1} = rX_i\left(1 - \frac{\mathrm{X_i}}{K}\right) \quad . \qquad (2)$$

The complexity of the dynamics in this model depends strongly on the value of the growth rate *r* (cf. Fig.1, upper panel). For a small growth rate, we obtain either a fixed point, in which the population does not change over the years or periodic behavior with different periods. For larger growth rate we obtain chaotic behavior in which it is impossible to predict the abundance of the population of species *X* in the next year. Though this model is rather simple, it possesses for certain growth rates a very complex irregular dynamics as depicted in Fig.1. (lower panel). This chaotic behavior limits the predictability of the system, since initially nearby trajectories diverge exponentially.

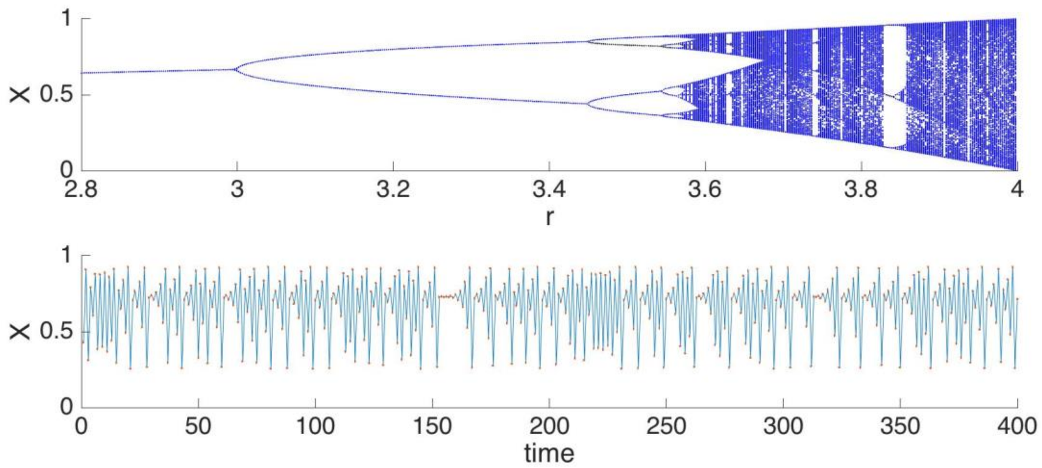

Fig.1. Discrete dynamics of a population restricted by limited resources described by the logistic map with carrying capacity K=1. Upper panel: Dynamics depending on the growth rate r. Lower panel: Time evolution of the population abundance in the chaotic parameter region, here computed at r=3.7.

As another example for modeling ecological processes, we mention predator-prey interactions, where the growth rate of the predator depends on the abundance of a prey called *X*. The formulation of the uptake or grazing rate has to fulfill certain biological empirical evidence. The grazing rate *f(X)* has to be zero if no prey is available, i.e. *f(0)=0*. Then it should grow with increasing prey availability, but finally saturate since the predator can eat only a certain amount of prey regardless of the number of prey species in case they are highly abundant. This would be well described by a function which is monotonously increasing for small values of *X* but finally go to a constant for large *X*. As an illustration we show in Fig.2 the mostly used mathematical formulations of the grazing rates of a predator depending on the prey [6].

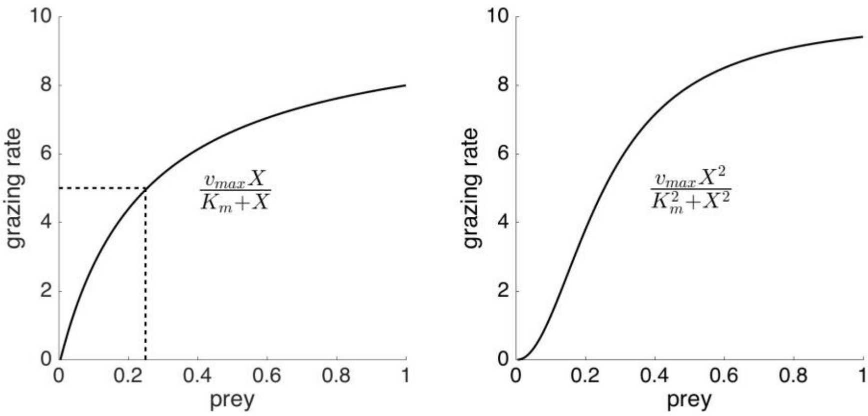

Fig.2. Different types of predator-prey interactions: Left panel: Holling type II, the dashed line indicates the line at which the prey abundance is equal to K_m and the grazing rate equals the maximum grazing rate v_{max}. Right panel: Holling type III

Depending on the complexity of the processes taken into account, these functions can be rather simple as described above or more complicated if e.g. the behavior of organisms like different hunting strategies depending on prey availability is additionally taken into account.

MODELLING HARMFUL ALGAL BLOOMS (HABS)

As already mentioned in the introduction harmful algal blooms constitute a major problem in many regions of the world's oceans. While there is an annual bloom of non-harmful species in spring, HABs occur either sporadically or if they appear on a regular annual basis, their magnitude, the exact timing of their onset, their specific location and geographical extent, their composition (i.e. which species dominates) as well as their duration and termination vary significantly from year to year. Therefore it is necessary to understand the mechanisms leading to triggering such harmful blooms in order to predict them. Several physical, chemical and biological factors are believed to contribute to the specific conditions under which HABs develop [7]. Moreover, climate change has led to a substantial increase in the number of HABs around the globe [8]. Possible causes for this increase are increasing input of nutrients into the oceans due to fertilizers used in agriculture and their subsequent transport into the ocean by river run-off, the warming of the ocean, changes in hydrodynamic flows due to climate change as well as the invasion of new species.

Several conceptual, empirical and numerical models have been developed to understand the main trigger mechanisms of harmful algal blooms [9, 10]. The complexity of those models depends on the number of processes and influencing physical and biological factors taken into account. We will focus here only on one model, which is particularly simple and can therefore be studied by high school students. Truscott and Brindley [11] formulated a model, which considers only the interaction between the harmful phytoplankton species as a prey and zooplankton as its predator. The mathematical functions taken into account for predator-prey interactions allow to explain dynamics as a nonlinear "excitable system". This model has been used to study red tides, i.e. HABs that are caused by a particular species, which changes the ocean color into red if they are very abundant. Excitability means here that a system which is usually in equilibrium is capable of developing a huge response in the form of a pulse when it is perturbed with a certain perturbation. A typical example for an excitable system is the excitation of a neuron, when it gets some input signal. The resulting dynamics consists of a fast growth of the so-called excitatory variable followed by a slower growth of the inhibitory variable. When the inhibitory variable is large enough, it starts suppressing the excitatory variable resulting in the end of the excitation and a return to the equilibrium.

The underlying model for a harmful algal bloom consists of two differential equations for phytoplankton P as prey and zooplankton Z as predator respectively:

$$\begin{aligned} \frac{dP}{dt} &= r \cdot P \cdot \left(1 - \frac{P}{K}\right) - \alpha \cdot \frac{P^2}{\mu^2 + P^2} \cdot Z \\ \frac{dZ}{dt} &= \gamma \cdot \alpha \cdot \frac{P^2}{\mu^2 + P^2} \cdot Z - d \cdot Z \end{aligned} \tag{3}$$

The first term in the phytoplankton equation describes the logistic growth of the phytoplankton with a rate r taking into the competition of phytoplankton cells for the limited resource K. The second term denotes the grazing of zooplankton cells upon phytoplankton. The grazing rate is modeled as an S-shaped Holling-type III function (cf. Fig. 2), i.e. it is very slowly increasing when prey is scarce, but then it is increasing quadratic with prey abundance until it saturates for large prey abundance. The time evolution of the zooplankton abundance is also formulated in terms of a balance equation in which the gain in zooplankton abundance is almost equal to the grazing term except for a prefactor γ which measures how much of the prey taken up is converted into predator biomass. The natural mortality of zooplankton – the last term in the zooplankton equation – is modeled with a rate d.

To illustrate the excitable dynamics we show in Fig.3. the time evolution of the response of phytoplankton and zooplankton after applying a perturbation in the zooplankton concentration. Truscott and Brindley [11] found that a zooplankton concentration below some critical level helps to bring the system into an "excited" state thereby initiating a bloom of phytoplankton. In the terminology of excitable systems, phytoplankton is the excitatory variable while zooplankton feeding upon it is the inhibitory variable.

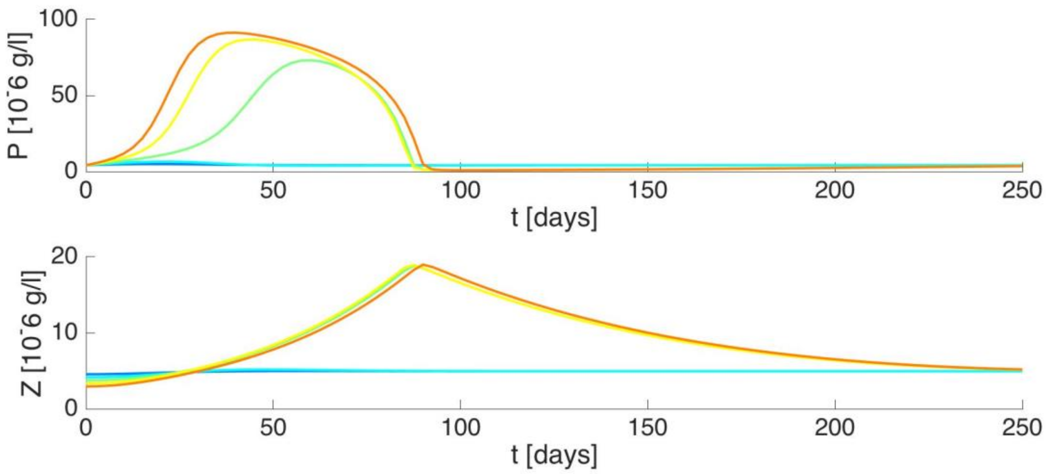

Fig.3: Time evolution of the Truscott-Brindley model, Eqs.(3), for different initial concentrations of zooplankton Z. Only low initial concentrations of zooplankton (orange, yellow and green curves) lead to a large response of phytoplankton P. The parameters for this simulation are: r = 0.3 day^{-1}, K = 108 g/l, α = 0.7 day^{-1}, μ = 5.7 g/l, d = 0.012 day^{-1}, γ = 0.05.

Let us now discuss the impact of the physical environment on the emergence of such harmful algal blooms. Two different important physical factors are considered in the following: temperature and hydrodynamic flows. While temperature influences the growth rates of plankton, hydrodynamic flows are responsible for the redistribution of nutrients and plankton in the water.

The growth of plankton depends crucially on the seasonal cycle. While in winter plankton abundance is low, it starts growing in spring when temperature and light availability are increasing. To take this factor into account, we introduce the temperature dependence of the growth rate via a factor, which scales the growth rate *r* based on the Arrhenius law as

$$r(T) = r \cdot Q_{10}^{(T-\bar{T})/10} \tag{4}$$

where Q_{10} is a species-dependent constant factor. This scaling means that a change in temperature by 10^o multiplies the growth rate by the factor Q_{10}. The temperature T varies with the seasonal cycle having a period of 365 days.

$$T(t) = \bar{T} + \Delta T \cos(\Omega t + \varphi) \tag{5}$$

Simulating the dynamics of the plankton model yields now a periodic behavior instead of the equilibrium we obtained before. When different initial abundances for the two species are selected we note that two different behaviors are possible: either we find a year in which no harmful bloom occurs or a strong harmful bloom develops (Fig. 4). This result reveals that we have two coexisting alternative states, years with and without blooms. Based on this finding we can explain the irregular bloom behavior observed in nature: When we consider a periodic temperature influence, that is equal each year, both, bloom and non-bloom dynamics are possible depending on the initial conditions. However, the temperature is only on average the same every year. In reality, small variations in temperature occur each year, so that the temperature on, say June 1, is not each year the same but possesses small fluctuations, which are caused by the weather patterns, which vary from year to year. Taking these fluctuations into account, the system is able to switch from non-bloom to bloom years and vice versa. This irregular switching resembles the dynamics of harmful blooms in nature [12].

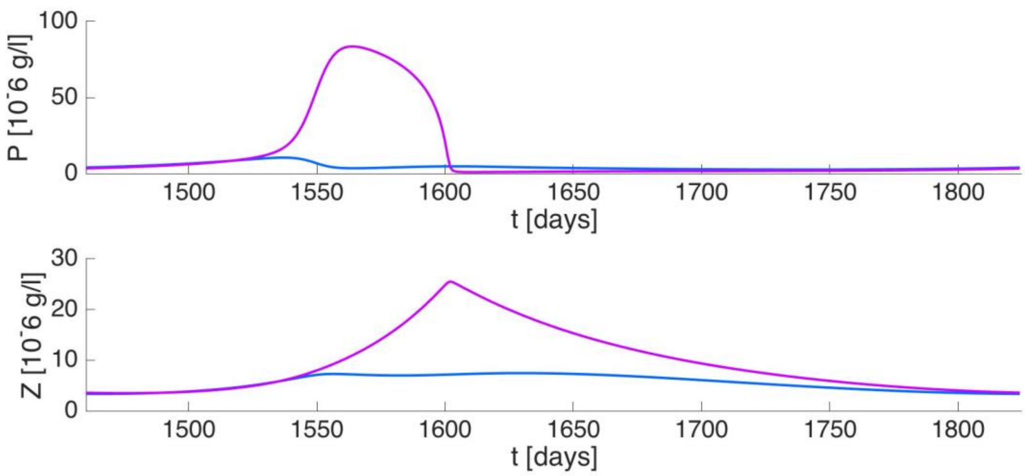

Fig.4. Abundances for phytoplankton (upper panel) and zooplankton (lower panel) for two different initial abundances: non-bloom year (blue), bloom year (magenta). Parameters are the same as in Fig. 3, $\Omega = 2\pi/365$ day^{-1}, T = 10^o, $\Delta T=6^o$, $\Phi = 0.59$.

Plankton blooms develop in the water column and are transported together with the inorganic nutrients – their food – by hydrodynamic flows. It is important to note, that hydrodynamic flows have in general very different time scales than biological processes. While the growth of plankton is on a time scale of days to weeks, ocean flow pattern travel in this time interval several hundreds of kilometers. To obtain an impact of flow patterns on plankton blooms one has to look for coherent structures in the flow which have a lifetime comparable to the biological time scales. Such structures are vortices in the flow, i.e. rotating flow patterns, which are present in all ocean flows and which possess different sizes and life times. Since the average lifetime of vortices is of the order of days up to several weeks [13], such structures can be essential for the emergence of plankton blooms. The role of vortices as incubators of plankton blooms has been shown using different food web models in simple kinematic flows [14] as well as in turbulent flows [15]. The rationale behind this behavior is the fact that the water is mostly confined within the vortex due to the very low exchange with the surrounding waters. Therefore, plankton can grow without much disturbance within the eddy. Moreover, such coherent structures in flows may lead to a separation of different species having different needs of nutrients. This separation opens up ecological niches for different species to coexist and hence to a sustained biodiversity in the ocean [16].

To demonstrate this dynamics, we address now the question of coupling the biological model to a simplified hydrodynamic model, which mimics basic properties of ocean flows. More specifically we show the emergence of a harmful bloom in a von Karman vortex street which develops in the wake of an island. Though the underlying velocity field in a two-dimensional spatial region is given analytically [17, 18], the numerical procedure to obtain these patterns is slightly more complicated and therefore omitted here. We only present the result for a plankton model, which contains two different species, harmful and a non-harmful one competing for the same resource. This model is a bit more complex but relies on the same assumptions than the previous one (for details cf. [19]). The emergence of a harmful algal bloom in a vortex is illustrated in Fig.5. showing the abundances of the harmful species blooming mainly within the vortex. Such localized blooms can also be observed in satellite pictures of plankton blooms around the world (cf. http://oceancolor.gsfc.nasa.gov/cms/).

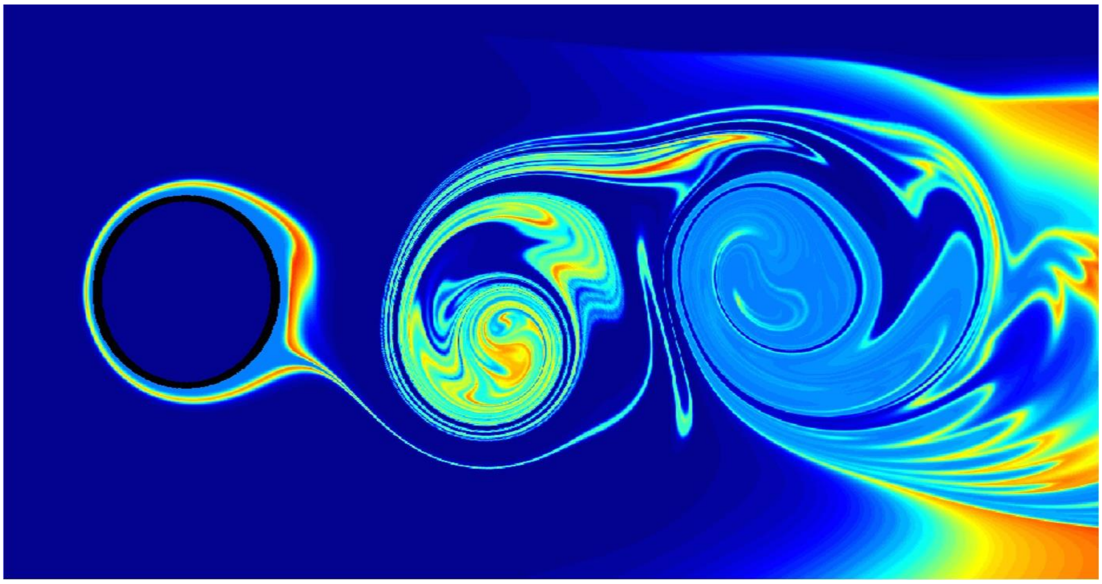

Fig.5. Phytoplankton bloom in a van Karman vortex street in the wake of an island: abundance is color-coded from blue for low abundance via green to orange for high abundance.

CONCLUSIONS

Interdisciplinary research on environmental problems requires an intimate interplay between different directions of science. To prepare high school students to those tasks and to get them acquainted to this much broader view on science it would be desirable if students would be exposed to questions, which are related to e.g. climate change. Utilization of such simple approaches to ecological systems as demonstrated here could be one way to start educating students in a comprehensive view on the earth system.

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