Modelling the effect of global warming on an aquatic ecosystem in central Italy

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Abstract

The concentration of atmospheric CO_2 is expected to double from 365 to 700 ppm by volume by the middle of the next century. Projections of CO_2 -induced climate change are less certain, but most of them predict a 2-4°C temperature increase, i.e. "global warming" [1]. On the other hand the effects of temperature in ecosystems are well known [2] regarding the solubility of O_2 and the limitations imposed to the photosynthetic process.

We study the simulation effects of such a temperature increase of 2-3°C in a structural mathematical model describing the dynamics of a coastal shallow water ecosystem located in the Natural Park of Circeo (Rome, Italy) [3].

Preliminary results of the simulations with the changed temperature show that in a 3 years time period an anomaly in the phytoplankton concentration will occur. Such behaviour, due to the stronger activation of photosynthetic activity, leads to an exceptional growth of phytoplankton and brings the whole system towards the extinction.

1 Introduction

Italian research on lagoons has been devoted, in the last years, to the systemic and integrated aspects of the analysis of this type of ecosystems [4,5,6]. In fact, even if each lagoon represents an ecological entity of its own, from a theoretical point of view some general properties of these ecosystems, such as high

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productivity, ecological complexity and ecological stability, have been recognised.

The high productivity is the consequence of strong energy fluxes including the photosynthetic active radiation and some type of mechanical energies (e.g. wind). The complexity of Italian coastal lagoons is not reflected in the specific diversity but in the high environmental diversity, the latter including forcing functions as solar radiation, temperature, wind, tidal cycle and land run off. The stability of Italian lagoons refers to their capability to damp the ecological perturbations by physiological and ethological adaptations; however one must not forget that the long term evolution of lagoon ecosystems that have a relatively brief geological life [7].

The present paper is based on the formulation and identification of a mathematical model referring to the main biotic and abiotic processes of a coastal shallow water lagoon situated in the National Park of Circeo (Rome, Italy). The aim of the work is to analyse the impact on this aquatic ecosystem of environmental perturbations that drive it from a stationary non-equilibrium state [8]. In fact, it is well known [9] that ecosystems dissipate energy in order to maintain their own *optimum operating point* [10] which is the equilibrium between organised and disorganised forces.

But, if the environmental drivers change in intensity, or in oscillation period, the system will modify its state and, after a period, will return to its original state or will remain in the new one.

2 The model

The model we refer is the following:

$$p = k_1 light(t)temp(t)pn - k_2 p - k_3 pz$$

This equation accounts for the phytoplankton dynamics (p): the first term refers to photosynthetic activity process, representing biomass production, the second term to respiration and natural mortality and the third term represents the losses due to grazing from zooplankton herbivore.

Specific conditions are accounted in the equation by means of threshold parameter functions, as follows:

$$k_{1}(wind) = \begin{cases} k_{1} & : wind \ge 1 \\ 0.5k_{1} & : otherwise \end{cases} \quad k_{2}(n) = \begin{cases} k_{2} & : n > 0.1 \\ 10k_{2} & : n \le 0.1 \end{cases}$$
$$k_{3}(light) = \begin{cases} 1 & : light = 0 \\ 0 & : light \ne 0 \end{cases}$$

 k_1 accounts for the fact that photosynthesis is inhibited at low wind regime, k_2 accounts for the increasing of mortality at low nutrients concentrations and k_3 accounts for avoiding grazing during the daylight time.

The second equation represents the zooplankton (z) dynamics:

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$$z = k_4 z p - k_5 z$$

The two terms of this equation represent the growth process for grazing on zooplankton and the losses due to respiration and natural mortality. The k_4 and k_5 parameters are defined as follow in order to consider the limitation to growth for low oxygen concentrations and the higher mortality for low food availability:

$$k_4(O_2) = \begin{cases} k_4 & : \ ox \ge 3\\ 0 & : \ otherwise \end{cases} \qquad k_5(p) = \begin{cases} k_5 & : \ p > 2\\ 100k_5 & : \ p \le 2 \end{cases}$$

The system is considered closed with respect to nutrients (n). Field experiments demonstrate that shallow coastal lagoons rarely have a remarkable limiting nutrient, in fact high primary production is rarely compatible with the very low concentrations of the nutrients that are found in the water column, therefore suggesting that the main nutrient source (especially for phytoplankton growth) must come from recycling and releases from the sediments. The differential equation describing nutrients related processes can be expressed as follow:

$$n = k_{14}(a_1 + a_2) + k_{15}(a_1 + a_2) - k_p k_1 light temp p n$$

accounting for both aerobic (first term) and anaerobic (second term) water and sediment mineralization and for the phytoplankton uptake due to photosynthetic process. The following conditions are also considered in order to avoid aerobic bacterial degradation for low oxygen concentrations (k_{14}) and, by contrast, to activate anaerobic processes (k_{15}):

Finally, the dissolved oxygen variable (O_2) is considered for its important ecological role in a large part of biological, chemical and physical reactions and processes.

$$O_{2} = k_{26}k_{1}light(t)temp(t)pn - k_{28}(a_{1} + a_{2}) - k_{29}(an_{1} + an_{2}) - k_{30}p - k_{31}z - \frac{k_{32}}{temp(t)}O_{2} + k_{27}wind(t)O_{2}$$

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Some terms referring to physical-chemical reactions such as wind re-aeration (last term) and inverse temperature dependent exchanges between dissolved and gaseous oxygen (the sixth term) compose the oxygen equation. The most important production is the primary production performed during photosynthetic process (the first term of the equation), while the fourth and fifth terms represent phytoplankton and zooplankton respiration: Finally the second and third terms account for aerobic (a_1+a_2) and anaerobic (an_1+an_2) bacterial consumption both in water and sediment.

An additional condition has been introduced in the re-aeration process in order to produce stronger re-aeration for high regime wind stress.

$$k_{27}(wind) = \begin{cases} 1.4k_{27} & : wind > 3\\ k_{27} & : wind \le 3 \end{cases}$$

There are three important physical properties for shallow water ecosystems considered in this model; the first is temperature that influences metabolism processes and oxygen solubility, the second is light that governs daily photosynthesis and the nocturnal feeding habits of the zooplankton, and third is the wind regime that is important for oxygen content, but also modifies organic matter availability in the water by determining sedimentation and re-suspension phenomena. Such functions are represented by means of periodic sinusoidal functions referring to field experimental data, for example temperature simulation at Italian latitudes is shown in Fig. 1.

Identification results of the model variables are described in Fig. 2.

3 Effects of increasing temperature and results

We analysed the effects of a small increase of 2-3 degrees in the water temperature values. The results of this modification can be seen in Figs. 3-5. Similar experimental analysis has been performed on an aquatic ecosystem stressed by warm water effluent from a nuclear power station. In this case [10] the result was the loss of two top predators, two lower predators and a dramatic change in the food-web in terms of cycling and trophic positions. In general, each species will optimise its resource utilisation and thus, over a different time scales, the ecosystem will tend to adapt to long-term environmental variability by species replacement. What it can be observed in this hypothetical simulation is a great increase in phytoplankton biomass during the third year (see Fig.3). This is followed by an exaggerated growth of the zooplankton species (see Fig. 4), which results during the fourth year, in a lowering of the phytoplankton concentration. This results finally in the extinction of the zooplankton population caused by the absence of prey. de la compañía de la comp

Conversely, the oxygen content is not strongly affected by the catastrophic phenomenon (see Fig.5); this fact is due to the action of the last term of the oxygen equation. In fact, the wind speed is able to re-aerate the water.

The phytoplankton biomass does not undergo extinction (see Fig.3) because its dynamics are regulated by the balance between light, nutrients and temperature. In our hypothesis light follows a regular pattern and nutrients content is never considered a limiting factor.



Figure 1. Simulation of annual water temperature. It is visible the night-day temperature variations.

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Figure 2. Annual dynamics identification of phytoplankton, zooplankton and oxygen concentration data.

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Figure 3. Four years simulation of phytoplankton equation with a 2.5 °C constant increase in the temperature function.







Figure 5. Four years simulation of oxygen equation with a 2.5 °C constant increase in the temperature function.

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