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Research paper

Temperature as a factor affecting fluctuations and predictability of the abundance of lake bacterioplankton

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ABSTRACT

Prediction implies the estimation of future states of dynamical systems on the basis of time series. Unavoidable uncertainty in making predictions stems from errors and fluctuations associated with making measurements, and also from the complexity of the dynamics themselves. To be predicted, the time series have to contain some kind of repeatability, which can be exploited in the course of forecasting. In particular, even irregular time series are often characterized by the repeatability that implies fuzzy recurrences of the states of the system under study. Recently, the recurrence quantification analysis was used in order to assess numerically the horizon of predictability of chaotic fluctuations of the phytoplankton abundance in the Naroch Lakes system consisting of three reservoirs, Lake Naroch, Lake Myastro and Lake Batorino (Medvinsky et al., 2015. Chaos far away from the edge of chaos: A recurrence quantification analysis of plankton time series. Ecol. Complex., 23, 61–67). Here, we present the results of the analysis of the dynamics of bacterioplankton populations, which inhabit the Naroch Lakes. We demonstrate that the dynamics are chaotic. The horizons of predictability of the bacterioplankton dynamics are shown to be equal to 4.8 months for Small Stretch of Lake Naroch, 4.6 months for Large Stretch of Lake Naroch, 4.7 months for Lake Myastro, and 3.4 months for Lake Batorino. Chaoticity of fluctuations in population abundance can be either an immanent feature of the dynamics or be related to environmental influences. In order to evaluate the action of changes in the environment on plankton dynamics, we assessed numerically the extent to which chaotic fluctuations of bacterioplankton and phytoplankton abundances in the Naroch Lakes were synchronized with temperature oscillations. With the use of the analysis of phase relations between bacterioplankton and temperature time series we show that the chaotic bacterioplankton oscillations are synchronized with water temperature oscillations, while chaotic fluctuations of the phytoplankton abundance are not synchronized with the temperature oscillations in Lake Naroch and Lake Myastro in contrast to the phytoplankton fluctuations in Lake Batorino, the smallest of the Naroch Lakes, where phytoplankton fluctuations are phase-locked by the temperature oscillations. We conclude that temperature is the factor that has significant impact on predictability of the bacterioplankton fluctuations, while dynamics and predictability of phytoplankton dynamics can apparently be controlled not only by the temperature but also by trophic interactions and nutrient supply.

1. Introduction

Predictability of natural processes is a subject of long-term hot debates. From the classical deterministic standpoint, the initial state of a system at a time t_0 completely determines the states for every time $t > t_0$ (Laplace, 1814). However, it is well known now

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that there is a limitation of predictability of subsequent system states that is related to unavoidable uncertainty in the initial conditions provided that the system evolution exhibits an intrinsic instability, i.e. rapid amplification of the initial uncertainty (Poincaré, 1891), or, in other words, if the system dynamics is chaotic. The dynamical chaos, which was found in physical, biological and ecological dynamical systems (Holden, 1986; Kaplan and Glass, 1995), is characterized by positive values of the dominant Lyapunov exponent, which quantifies the inherent instability of the chaotic dynamics (Ott, 2002). As a result of the instability, predictability of the chaotic fluctuations is limited; the prediction is possible just up to a predictability time, the horizon of predictability (Boffetta et al., 2002).

The chaotic dynamics, along with sensitivity to initial conditions, are characterized by a recurrence. The recurrence implies that the state variables even though been unable to return to their previous values can nevertheless recur very closely to these values. In order to analyze the recurrences of dynamical systems, a method of recurrence plots was put forward (Eckmann et al., 1987; Zbilut and Webber Jr, 1992); see Section 2 for more details. The recurrence quantification analysis allows, in particular, assessing numerically predictability of chaotic fluctuations (Marwan et al., 2007).

Recently, we applied the recurrence quantification analysis in order to examine phytoplankton dynamics in the Naroch Lakes, Belarus. As a result, it has been shown that the phytoplankton dynamics are chaotic. The recurrence quantification analysis led us to assume that even without any tangible environmental impacts interspecific interactions across trophic levels can cause emergence of chaos in the plankton dynamics (Medvinsky et al., 2015). This is not to say, however, that habitat conditions have no effect on the dynamics of planktonic populations. Indeed, any population is influenced by not only interspecific interactions inside the community to which the population belongs but also by environmental factors, primarily temperature (Royama, 1992). The question arises, what is the relative contribution of interspecific interactions and environmental factors to the character and predictability of population dynamics?

The answer to this question can be approached by contemporary methods of the analysis of time series. In the given work we apply the recurrence quantification analysis and the analysis of phase relations between time series in order to analyze the data of long-term monitoring of fluctuations of both the bacterioplankton and phytoplankton abundances in the system of Naroch Lakes. This lake system consists of three water bodies, Lake Batorino, Lake Miastro, and Lake Naroch, which in turn is subdivided into Large Stretch and Small Stretch (Fig. 1). All the lakes differ in morphometry and hydrology (Table 1). However, there is a feature common to all these reservoirs: they are polymictic. In other words, these reservoirs are prone to considerable wind mixing (Lampert and Sommer, 2007).

Table 1
The main characteristics of the lakes.

Characteristics	Lake Naroch	Lake Myastro	Lake Batorino
Surface area (km^2)	79.6	13.1	6.25
Water volume (millions m^3)	710.0	70.1	18.7
Depth (mean/maximum) (m)	8.9/24.8	5.4/11.3	2.4/5.5
Total water exchange (years)	10–11	2.5	1.0

We demonstrate that along with phytoplankton dynamics, which has been revealed to be chaotic (Medvinsky et al., 2015), the dynamics of bacterioplankton inhabiting the Naroch Lakes are chaotic as well. Besides, we show that the chaotic bacterioplankton oscillations are synchronized with temperature oscillations, while chaotic fluctuations of the phytoplankton abundance are not synchronized with temperature in Lake Naroch and Lake Myastro, in contrast to the phytoplankton fluctuations in Lake Batorino, the smallest of the Naroch Lakes.

2. Materials and methods

2.1. Sampling and sample analysis

The bacterioplankton sampling and the measurements, which resulted in the time series presented in Fig. 2, were carried out in 1995–2014. Samples were collected monthly at monitoring points during the vegetative season (from May to October) using a two-liter Ruttner sampler. The samples were collected from six different depths (0.5, 3, 6, 8, 12 and 16 m) in Lake Naroch, from four depths (0.5, 4, 7 and 9 m) in Lake Myastro, and from three depths (0.5, 3 and 5 m) in Lake Batorino. The water samples from all the depths were mixed in such a way that the water volume of each level (depth) in the mixed sample was proportional to the fraction of the level in the total water volume in each of the lakes according to bathymetry. Samples were fixed with 0.4% formalin. One milliliter of each of the samples was withdrawn, mixed with one milliliter of Acridine orange and then placed on the Nucleopor nuclear filter with pore diameter of 0.2 μm. Filters were pre-kept in the solution of Sudan Black B during 12 h to suppress intrinsic luminescence and then they were washed with distillate water and dried. Each filter was placed on the slide with nonluminiscence vaseline oil and covered by a coverslip. The top surface of the coverslip was in turn covered by nonluminiscence vaseline oil. The

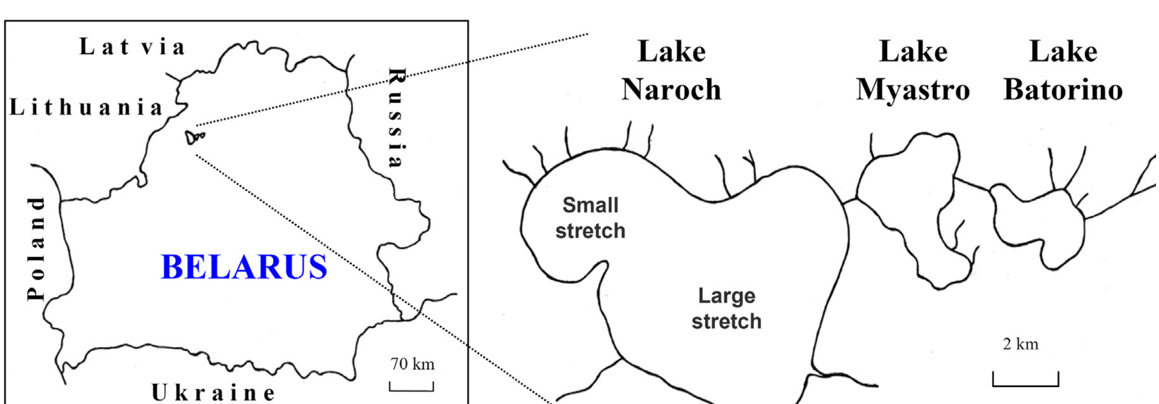

Fig. 1. Geographical location of the Naroch Lakes. The samples were collected in Small Stretch (54°53′18″N, 26°43′20″E) and Large Stretch (54°51′18″N, 26°46′74″E) of Lake Naroch, in Lake Myastro (54°52′02″N, 26°52′83″E), and in Lake Batorino (54°50′80″N, 26°80′06″E).