CORVINUS
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Modelling of the phenomena of climate change in a theoretical aquatic ecosystem

PhD thesis

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INTRODUCTION

During the past years, decades it is observable that climate change has an impact on our everyday life, because extreme weather conditions occur more frequently as well as in our country, in Europe and all over the world.

The latest IPCC-report (2007) points out that the global average temperature of the Earth has risen cc. 0.6 ^{0}C degree during the last 100 years, and 2-4 ^{0}C temperature rising is expected by 2100. Climate change has an impact on the all parts of our economic and social life, and on natural ecological systems. Besides the treating of climate change it is important to deal with the biodiversity.

There is a dynamical equilibrium between the climate and ecosystems at natural systems. If the system is affected by anything, then there will be a response to maintain the equilibrium. Its degree could be a sudden effect or gradual. Nowadays it looks that the unpredictable, sudden changes will be dominant.

In the course of my research a theoretical freshwater algae-community model has been developed (TEGM, Theoretical Ecosystem Growth Model). The result and the way of the equilibrium evolved in various, theoretical and real climate conditions are examined with the help of the model.

AIMS

The base of my PhD work is to develop a complex strategic climate-ecosystem model in order to examine the effects of changing temperature on the contents and diversity of the theoretical ecosystem.

- The aim is to create a theoretical ecosystem model to examine the effects of changing temperature in climate.
- With the active participation of the theoretical ecosystem in the global carbon cycle there is opportunity to examine the control ability of the climate at the community. I would like to develop a simple model to examine the control effect.

After building up the strategic models the aim is to analyse the effects of global warming and temperature fluctuations in case of the theoretical freshwater ecosystem.

THE ELABORATED THEORETICAL ECOSYSTEM GROWTH MODEL (TEGM)

During my research a theoretical ecosystem was studied by changing the temperature variously. An algae community consisting of 33 species in a freshwater ecosystem was modelled. The conceptual diagram of the TEGM model (Fig. 1) describes the mathematical calculations during the modelling process. The model has two important input parameters. One is the various reproductive functions, the other is functions of the temperature patterns.

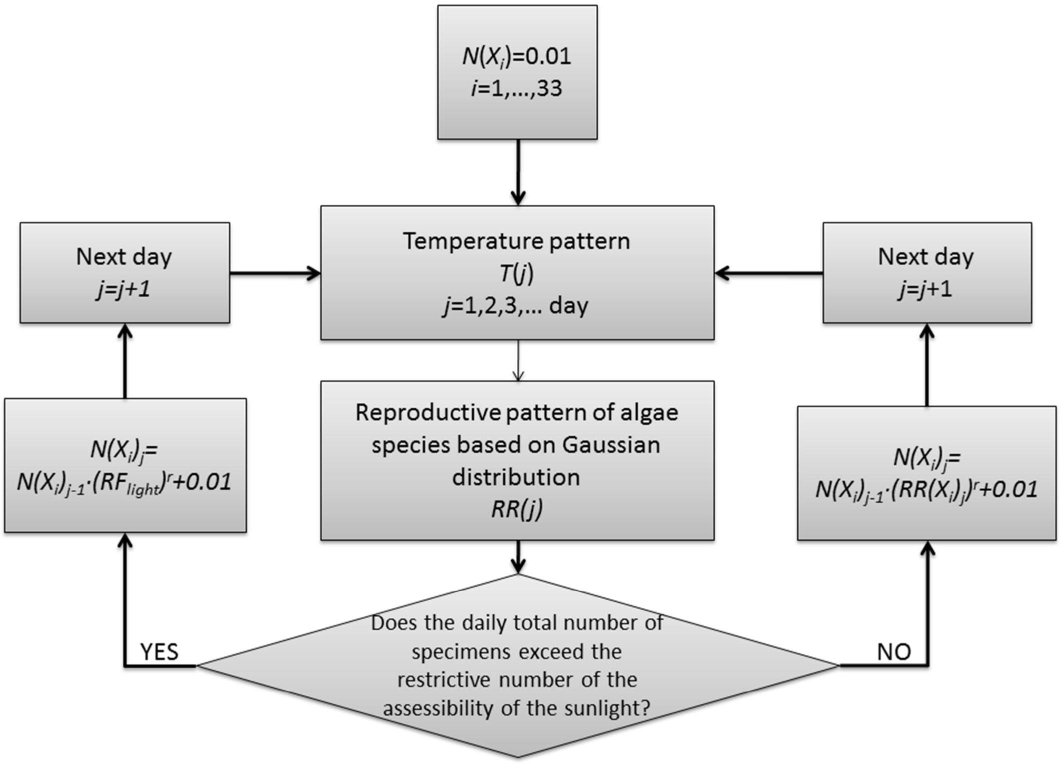

Figure 1: Conceptual diagram of the TEGM model (*RR*: reproduction rate, *RF*: restriction function related to the accessibility of the sunlight, $N(X_i)$: the number of the i^{th} algae species, *r*: velocity parameter)

Rivalry begins among the species with the change of temperature. In every temperature interval, there are dominant species which win the competition. The increase of the population is not infinite because of the restrictive function of the model. The ecosystem reaches a dynamic equilibrium state for an input temperature. In the course of this equilibrium the following output parameters are examined: the dominant species and their numbers, the value of use of resources, the diversity of the ecosystem and the duration of reaching the equilibrium.

Algae species are characterised by the temperature interval in which they are able to reproduce. This reproductive feature depends on their temperature sensitivity. There are four types of species based on their sensitivity: super generalists (SG), generalists (G), transitional species (T) and specialists (S). The temperature-optimum curve originates from the normal (Gaussian) distribution, where the expected value is the temperature optimum.

The examined temperature range corresponds to the temperature variation in the temperate zone. Thirty-three algae species with various temperature sensitivity can be seen in the Fig. 2. The daily reproductive rate of the species can be seen on the vertical axis, which means by how many times the number of specimens can increase on a given temperature. This corresponds to the reproductive ability of freshwater algae in the temperate zone.

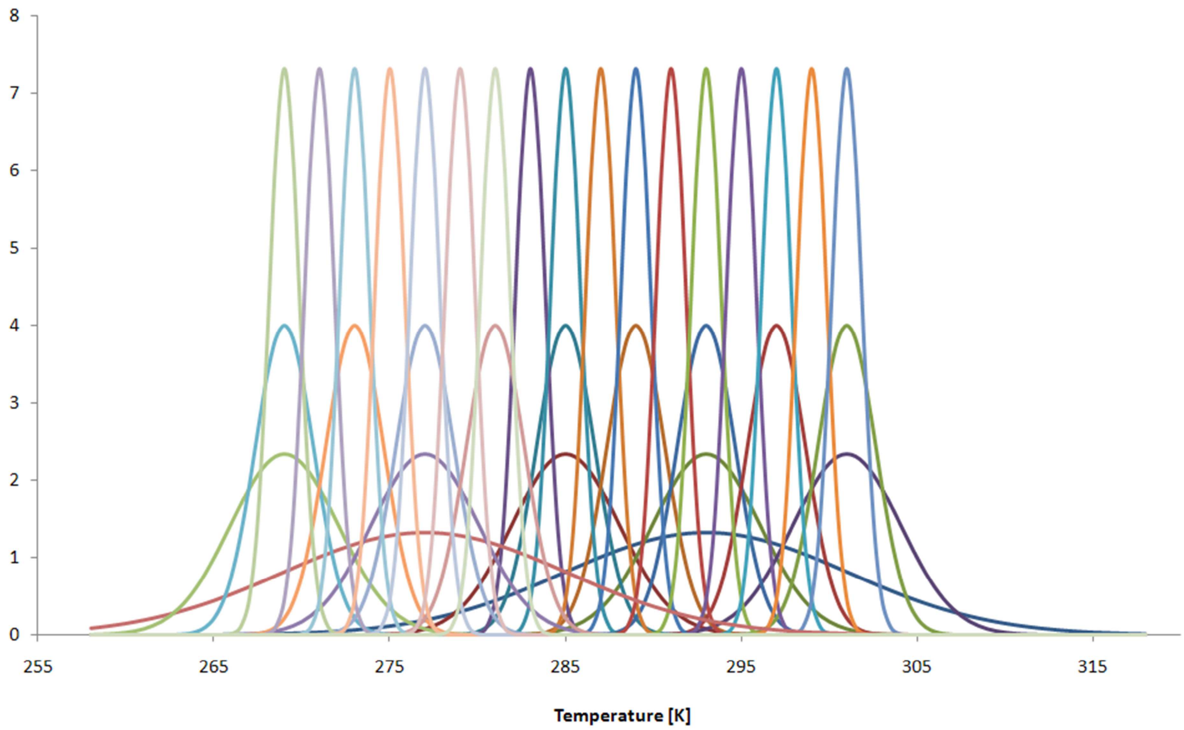

Figure 2: Reproductive temperature pattern of 33 algae species

Since the reproductive ability is given the daily number of specimens related to the daily average temperature is definitely determinable. We suppose 0.01 number of specimens for every species as starting value and the following minimum function describes the change in the number of specimens:

$N(X_i)_1 = 0{,}01$ for every i=1,2, …, 33 species,

where $N(X_i)$: the number of specimens of the i^{th} species

$$N\left(X_i\right)_j = N\left(X_i\right)_{j-1} \cdot Min\left\{\left(RR\left(X_i\right)_j\right)^r ; \left(RF_j\right)^r\right\} + 0.01 \qquad (1)$$

where

j :is the number of the days (normally j=1,2,…,10593; for 29 years);

$RR(X_i)_j$: is the reproductive rate of the X_i species on the j^{th} day;

r: is the velocity parameter (r=1 or 0.1);

$$RF_k = a^{\left(1-\left(\frac{\sum_{i=1}^{33} N(x_i)}{K_k}\right)^{\nu}\right)} \qquad (2)$$

k=1,2,…,366 , this is the sequential number of the given year (year-day).

The restrictive value of reaching the sunlight (K_k) was set to 10^7 value in the first phase of the simulation studies (TEGMa model), in the second phase the intensity of the sunlight changing during a year was considered (TEGMb model):

$$K_k = d_1 \cdot \sin(d_2 \cdot k + d_3) + d_4 + \varepsilon \qquad (3)$$

where d_1=4950000, d_2=0,0172, d_3=1,4045, d_4=5049998, ε*:* has uniform distribution int he interval of (-50000,50000).

The constant values of the K_j restrictive function is set in a way where the period of the function is 365.25, the maximum place is on 23rd June and the minimum place is on 22nd December. (These are the most and the least sunny days.)

Functions of temperature patterns and special functions

In my researches the distribution of the algae community of a theoretical freshwater ecosystem is examined by changing the temperature. The temperature was changed according to plan in order to estimate the various effects separately. The duration of the simulation was usually 29 year in the experiments. Two experiment series were run related to the dual value of the velocity parameter.

The examined temperature patterns are as follows:

- Constant temperature (293K, 294K, 295K)
- The temperature changes as a sine function over the year
- Historical and future climate patters
    - Historical temperature data in Hungary (1960-1990)
    - Future temperature data in Hungary (2070-2100)
    - Temperature values in Budapest for 140 years long (1960-2100)
    - Analogous places related to Hungary by 2100
    - Historical daily temperature values from various climate zones

The reaching the equilibrium state of the theoretical ecosystem model was examined by three special functions. One of them is the Dirac delta function, which can be modelled as a large change in temperature lasted small time. The other is the step function which modelling remaining significant change in temperature. The third one represents the slowly increasing temperature day by day.

It is important to study the effects of daily temperature fluctuations. This was modelled as the disturbance has a uniform distribution (between ±1K… ±11K). During the simulation the given random fluctuation on the constant, sine and increasing temperature pattern was analysed.

Mathematical description of the control ability

The environment, the local and the global climate are affected by the ecosystems through the climate-ecosystem feedbacks. The feedback ability of the theoretical ecosystem model are examined through the global carbon cycle.

The theoretical ecosystem is imagined that the amount of the biomass (a part of the carbon stored by the ecosystem) participates in the build-up of the plants or affects the carbon-content of the atmosphere. It is supposed that the plants alter into atmospherical CO2 at the moment of their ruination. The net primer production (NPP) is considered as biomass production of plants.

The control effect of the theoretical ecosystem is made for the historical temperature data of Budapest, for TEGMb model, in case of r=1. During the simulation there are some used temperature data series. These are as follows:

T(0): are the data where there is no feedback of the ecosystem on the climate, and there is not any anthropogenic effect.

T(1): are the data where there is feedback of the ecosystem on the climate, this is related to the measured, historical temperature data.

T(2): are the data where there is no feedback between the ecosystem and the climate, but the anthropogenic effect exists.

T(3): are the data series where there are both the feedback and anthropogenic effects.

RESULTS OF THE TEGM SIMULATION STUDIES IN CASE OF VARIOUS CLIMATE CONDITIONS

The ecosystem answers according to our expectations on hypothetical constant temperature. The use of resources is nearly 100%. During TEGMa simulation with faster reproduction the equilibrium exists in 32-34 days, in case of 293K and 295K faster, than in 294K. The ecosystem, which has r=0.1 velocity parameter, reaches the equilibrium during 151 days in 293 and 295K, and 187 days in 294K.

The appearing of the species during the simulations depend on the amplitude of the sine function. In case of s_1=2 there is a few specimens. With the increase of the annual temperature fluctuation there are special communities according to the season (spring, summer, autumn, winter).

In the course of historical temperature pattern in Hungary the equilibrium has been reached. The faster ecosystem has a lot of specialists and some transient species. During summer, there is stationary temperature; therefore, the slower and the faster ecosystems show quite a similar picture.

Analysing the 140-year data series it could be examined what kind of seasonal dynamic alterations are resulted by the climate change. It is stated by the simulation of the strategic model using the HC A2 scenario that from November to May there could not be significant changes in the number of specimens and in the seasonal dynamics. There could be seen serious changes from June to October but not in the number of specimens, only the species will exchange. The annual total number of specimens shows a continuous decreasing during the 140 years (Fig. 3.), and the diversity of the theoretical ecosystem also decreases (Fig. 4.)

The simulation results of analogous places show that the species composition is similar to the historical data in case of Turnu Magurele, similarity exists with future estimations in winter. Present-day temperature of Cairo shows analogy with MPI 3009 predictions by 2070–2100 rather well.

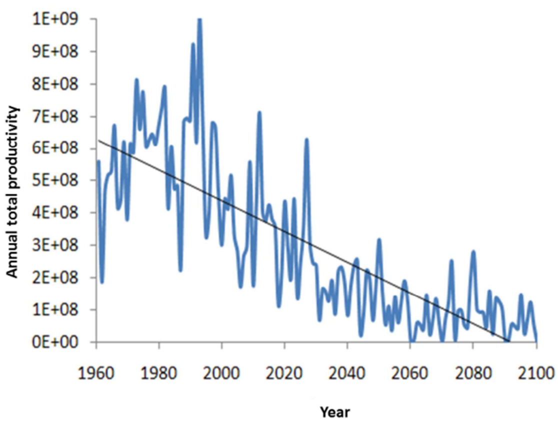

Figure 3: The change in annual total productivity during the 140 years (TEGMb model)

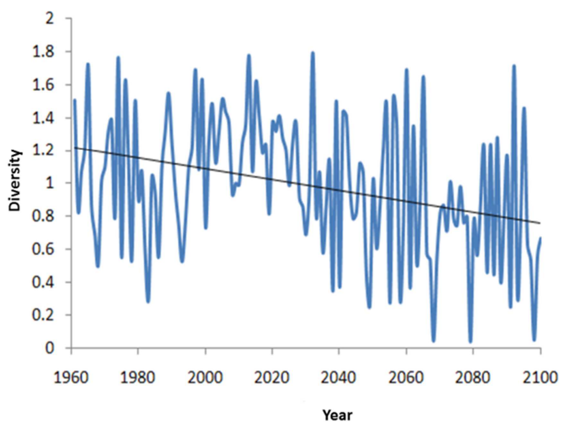

Figure 4: The change in diversity during the 140 years (TEGMb model)

The annual total number of specimens and the diversity values for various climate conditions are presented in Fig. 5. The simulation has been repeated 10 times, therefore the averages of the characteristics and the calculated deviation for the diversity values can be seen in graph. Regarding the annual total number of specimens it is stated that the species are in maximum numbers in case of ecosystems which has faster reproduction. There is only one climate condition (Bangui) where the maximum value in the number of specimens has been reached in case of slower reproduction. The difference between the annual total number of specimens in cases r = 1 and r = 0.1 is the largest at climate pattern of Ulan Bator. The reproduction of the simulated experiments is sufficient in most cases. The diversities are between 1.5 and 2.5 in case of r = 1 velocity parameter except for the case of Bangui which has 0 diversity value.

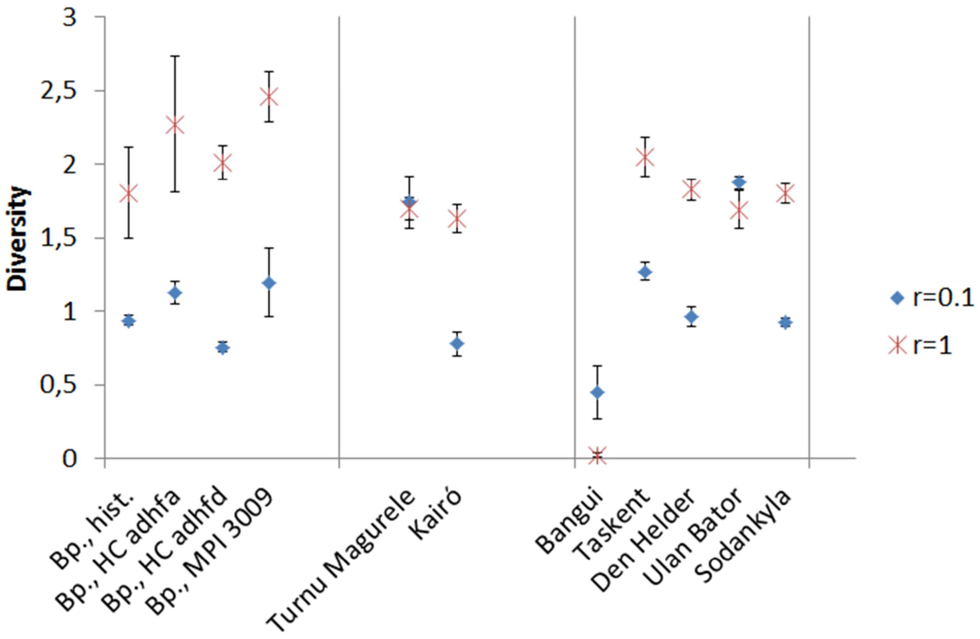

Figure 5: Diversity values for historical and future temperature in case of TEGMb model, with both velocity parameter (The simulations were made 10 times, the average of the diversity and the standard deviation are drawn)

THE EFFECT OF DISTURBANCE ON THE ADAPTABILITY OF THE COMMUNITY IN TEGM MODEL

Examination of impulse unit

Comparing the faster and the slower ecosystems it is stated that the change in the composition of the equilibrium state is similar, if in case of *r*=1 the system is given 3K impulse and in case of *r*=0.1 10 K temperature impulse. If 15 K or more impulse is given in case of faster ecosystem, then the composition of the species are the same before and after the interference. (Fig. 6)

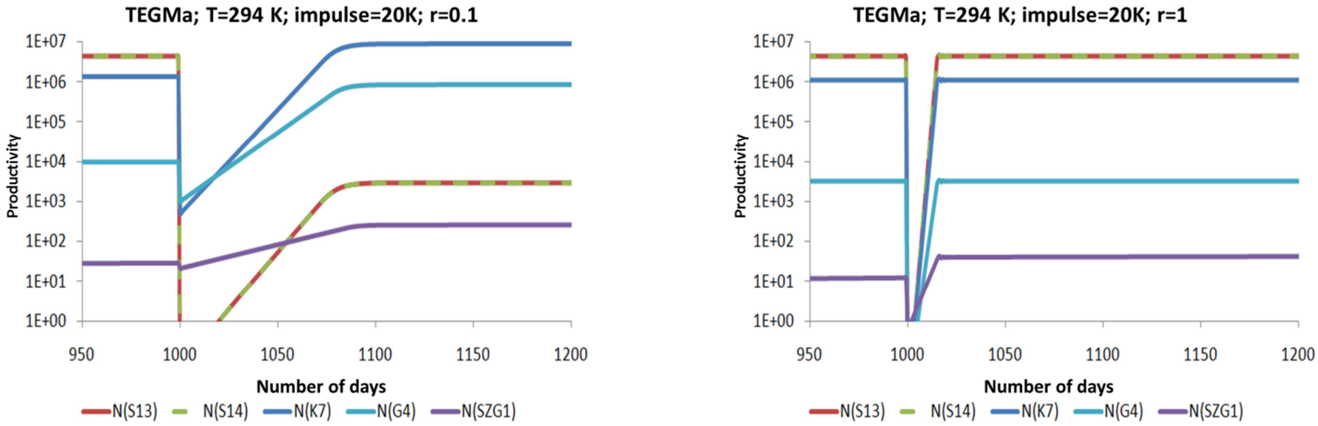

Figure 6: The effect of 20 K temperature impulse on the 1001th day of the simulation (in case of *r*=0.1 and 1, TEGMa model, T=294K)

It is important to study how the diversity and the adaptability works out in the course of smaller impulses. The distribution of species and the diversity of the theoretical ecosystem strongly depends on the setting value of the velocity parameter. The diversity of the faster ecosystem increases with smaller temperature impulses (3K, 5K) during TEGMa simulation. The diversity continuously increases during the 30 years of simulation in case of 5 K impulse and decreases in case of 3 K impulse using the TEGMb model. There are an increase in the diversity value in the course of larger impulses (10K, 15K, 20K) for the slower ecosystem in both, TEGMa and TEGMb cases. The evolving time of the new equilibrium state is the slower where the simulation has *r*=0.1, *T*=294 parameters.

Examination of step unit

The value of the constant temperature function was changed at the 1001th day of the simulation. At 293 K temperature the conditions are suited for the S13, K7, G4 and SG1 species optimum reproducibility. In this temperature the composition does not change.

On the effect of 1 K temperature ramp at 294 K constant temperature the composition of equilibrium does not change significantly in case of both the slower or the faster ecosystem (S14 appears with 10 number of specimens).

Observing the Shannon diversity values of the ecosystem it is stated that the diversity value, which belongs to the new equilibrium state, moves through a local maximum value depending on the temperature.

Examination of ramp temperature function

During ramp temperature function the value was daily increased from 268K continuously with various amounts (0.0001K…0.01K). It can be seen the appearance of some species depending on gradient. The local maximum values of the diversity exist where the specialist and the generalists have just exchanged with each other.

Daily random fluctuation

In case of constant temperature pattern the results of the simulation study can be seen in Fig. 8, which is the part of the examinations where the random fluctuations were changed until ± 11K. The number of specimens in the community is permanent and maximum until the daily random fluctuation values are between 0 and ±2K. Significant decrease in the number of specimens depends on the velocity factor of the ecosystem. There is sudden decrease at ± 3K fluctuation in the case of the slower processes while the faster ecosystems react at about ± 6K random fluctuation. The diversity of the ecosystem which has faster reproductive ability shows lower local maximum values than the slower system in the experiments. The degree of the diversity is greater in the case of r=0.1 velocity factor than in the case of the faster system. If there is no disturbance, the largest diversity can be presented found at 294 K for both speed values. If the fluctuation is between ± 6K and ± 9K, the diversity values are nearly equally low. In case of the biggest variation (± 11K) the degree of the diversity increases strongly.

In case of sine temperature function the annual total number of specimens change with the annual fluctuation (s_1, the amplitude of the sine function) and with daily random fluctuation (0…±7K). The two type fluctuation results in that the number of specimens and the use of resources decrease strongly at ±7K random fluctuation.

At linear increasing temperature pattern the value of the use of resources does not decrease to zero value in case or larger gradients (0.005K/day and 0.01 K/day) and large random daily fluctuation (±7K). This decrease happens in case of smaller gradients. This is because the supergeneralists are less sensitive for the daily random fluctuation. This does not appear in case of slower ecosystems.

THE CONTROL EFFECT OF THE THEORETICAL ECOSYSTEM ON THE CLIMATE

The composition of the ecosystem determines the feedback effect, the effect of temperature control. In the first case (T(0)) the evolving ecosystem causes 1.5-2.5K decrease in the temperature in July, August and September. So the theoretical ecosystem could have cooling effect in summer until 3K temperature, in fall until 2K temperature; while in winter and spring there is less amount of biotic feedback. To take into account the anthropogenic effect it can be stated that the feedback, the ‘cooling effect’ of the ecosystem is less realized, the maximum difference is (T(2)-T(3)) 1.3 K temperature difference. In fall some shifts can be seen, the temperature can decrease in February and in March.

NEW SCIENTIFIC RESULTS

- TEGM model and the calculation scheme for its application has been prepared. Changes in the composition of the ecosystem could be examined with the help of the theoretical mathematical model.

<u>Main observations based on the simulation of TEGM model in case of various climate conditions</u>

- The simulation experiments at hypothetical constant temperature (293K, 294K, 295K) do not reach the equilibrium state in 30 years (TEGMb model, r=1). In case of the ecosystem had smaller reproducibility (r=0,1) there is a decrease in number of specimens sooner, and there are larger changes in the biodiversity, than in case of faster ecosystem. The number of specimens has already decreased in case of smaller fluctuations significantly, these communities are more diverse.
- In case of sine temperature pattern, it can be stated that decreasing the value of the velocity factor, the number of specimens significantly decreases. Meanwhile, the amplitude of the temperature function is quite small (s_1=2 or 8); there are some specimens, but increasing the amplitude, the species disappear. Small increase in the amplitude of the sine temperature function raises the diversity value (similarly as constant case).
- The total number of specimens in a year decreases for the given species in the future (using estimated weather data series by 2070–2100, MPI 3009, HC adhfa and HC adhfd), the degree of decrease is different among the various results. Comparing the Hungarian historical data with results of predictions of analogous places by 2100 (Cairo, Turnu Magurele), it can be said that the total number of specimens is the same, but it is a little higher in case of Cairo. During the slower simulation process, the total number of specimens decrease in case of Turnu Magurele, and in Cairo, there will be significantly more specimens (10 times more). Comparing the historical data with the two predicted temperature data (HC adhfa, MPI 3009) it is stated, that the diversity value calculated for 1 year increases, but HD adhfd data shows similar picture. This observation is analogous in case of faster and slower process.

The effect of disturbance on the adaptability of the theoretical ecosystem

- The new equilibrium state evolved on the effects of small and medium temperature impulses differs significantly from the state before the interference.
- Analysing the effect of temperature step it is stated that the composition of the ecosystem being equilibrium at base temperature determines, what kind of the diversity of the ecosystem will be.
- If the temperature changes linearly and slowly in time, then the If the temperature slowly changes according to a linear function, the specialists and transient species favouring the given temperature exist in the ecosystem. The super generalist occurs in very little amount in simulations with little fluctuations.
- Generally it can be stated that specialists disappear from the dominant species by ±1K random fluctuation, generalists exist till ±6-7K fluctuation, but above this fluctuation only the supergeneralists are till maximum ±10-11K fluctuation.
- During the simulations with the TEGM model the Intermediate Disturbance Hypothesis can be observed in case of slower and faster ecosystems. Increasing the daily of annual temperature fluctuation the diversity increases by small disturbance, then decreases with the further increase of disturbance.

Control effect of the climate-ecosystem

- In case where there is no anthropogenic effect the ‘cooling’ effect of the plants is up to 2.5K dependent upon the seasons, months. Considering the amount of the anthropogenic carbon and the global warming it is stated that the ‘cooling’ effect of the living Earth, the plants decreases up to 1.3 K temperature after 100 years.

DISCUSSION

The developed competitive theoretical ecosystem model reacts as expected for the various temperature patterns. Analysing the results of constant temperature, it can be stated that the specialists and transient species adapted best to the given temperature are dominant during the competition, but generalists and super generalists occur rarely.

The increase of the daily random temperature fluctuation favours for the generalist species. During the simulation study of a theoretical community made of 33 hypothetical algae species the temperature were varied and it is realized that the species richness is responding with an intermediate disturbance hypothesis (IDH) pattern.

Comparing the Hungarian historical data with the regional predictions of huge climate centres (HC, MPI) it is stated that the newer estimations (such as HC adhfa, HC adhfd and MPI 3009) show a decrease in number of specimens in our theoretical ecosystem. The results of the 140-year temperature data show that there will be changes in summer, the diversity of the ecosystem decreases. The results are in consequence with the facts that the amount of the biomass and diversity could decrease with the increase of average temperature.

The artificial freshwater algae-community reacts differently on the effect of temperature impulse depending the amount of the impulse (1K-100K). If the ecosystem is disturbed by medium temperature impulse then the evolved equilibrium state is different from the expected on the given temperature. 1 K temperature step do not change the composition of the ecosystem at 293K and 295K, the S13 and S14 species remain the strongest during the competition. At 294K constant temperature the S14 genre extrudes the others in case of temperature step.

If the temperature slowly changes according to a linear function, the specialists and transient species favouring the given temperature exist in the ecosystem. The largest diversity value can be observed during the competition where the species has just exchanged, i.e. one species extrudes the other, and the community transforms significantly.

The effect of the random temperature fluctuation between days was examined with TEGMb model. There are two local maximum in the diversity values at constant temperature pattern increasing the random temperature fluctuation between days. The shape of the IDH local maximum curves shows that it increases slowly and decreases steeply. The main reason of this pattern is because the competitions between the various species. If the environmental conditions are better to a genre the existing genre disappears faster, which explains the steeply decreasing in the diversity values after the competition.

The productivity correlates with the amount of the atmospherical CO_2, the growing greenery binds carbon from the air. In case where there is no anthropogenic effect the ‘cooling’ effect of the plants is up to 2.5 K dependent upon the seasons, months. Considering the amount of the anthropogenic carbon and the global warming it is stated that the 'cooling' effect of the living Earth, the plants decreases up to 1.3 K temperature after 100 years. This means that there will be maximum 1.2 K increase in temperature except for the anthropogenic warming due to the control ability of the plants for the climate.

The developed TEGM theoretical algae-community strategic model was adapted to real data from Danube as Danube Phytoplankton Growth Model (DPGM) by Sipkay et al. (2008, 2009, 2010). During the optimization process the best fit was reached with the linear combination of 21 theoretical population in the simulation of the total phytoplankton biomass in order to make case studies examining the effects of the global warming.

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