The thermal response of small and shallow lakes to climate change: new insights from 3D hindcast modelling.

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Author's response

First of all, my co-authors and I would like to thank the Reviewers and the handling Editor for the time and interest taken in evaluating our work, as well as for their suggestions that helped improve our analysis.

In the present work, the thermal regime of a shallow urban lake is reconstituted over six decades (between 1960 and 2017) with a 3D thermal-hydrodynamic model, after calibration and validation. Simulation results are analyzed over time (for long-term monotonic trends), and space (for spatial heterogeneity), through a series of indices that characterize the stratification dynamics and highlight the relation between temperature and primary production. The work was initially submitted on the 10th July 2020, and has already undergone a first round of reviews.

As stated by the Editor in his final report, both reviews were constructive and quite similar in their major concerns, to which we have already addressed a first response (available at the interactive discussion page: https://esd.copernicus.org/preprints/esd-2020-51/#discussion). Both reviewers asked some clarifications on the choice of constant values for some of the parameters used in our modelling design (in particular the Secchi depth and sky cloudiness). However, no substantial remarks were made on the technical robustness of our working design.
The major concern regarded the novelty of this study, as the most distinctive element of our work, the 3D modelling approach, was not adequately exploited. Furthermore, doubts were raised on the biological relevance of the two indices chosen here as proxies for biomass production (namely, the growing degree days (GDD) and the number of growing days (NGD)). In particular, the choice of the temperature threshold for the calculation of the two indices was questioned as well as the lack of an upper limit for growth taking into account high-temperature stress.

According to the main remarks pointed out in the reviews and summarized above, we substantially modified the analysis of model results, with the objective of better highlighting in the revised version the potential of a 3D modelling approach and its relevance even for small water bodies. Namely, the main changes we have done concern the exploitation of the 3D results and the definition of the indices representing primary production. In particular, compared to what was initially suggested in our first reply to the reviewers, the analysis of the 3D results was expanded and has surpassed the ideas initially proposed in the reply.

In this revised draft we propose a more structured study of the spatial heterogeneity that focuses on the distribution of both stratification and potential primary production. This was done, after the Editor's and reviewers suggestions, by plotting the probability density function of some indices, which allows to visualize the evolution over time of the spatial distribution of these indices. The proxies for primary production were also changed, according to the remarks of the reviewers. An upper limit has been added in the expression of the growing degree days (GDD) to account for a possible stress induced by high temperature. The number of growing degree days (NGD) is no more considered in the revised version of the paper. It has been replaced by an other index that is the mean annual value of the thermal growth rate of cyanobacteria.

The major changes made to the original draft are described hereby in a detailed point-to-point list. In the following paragraphs, italics is used for extracts of the initially submitted version, while the blue colour identifies the parts of the text coming from the revised manuscript.

Indices for primary production

In the first version of our manuscript, two indices were used to characterize primary production from a thermal standpoint: the growing degree days (GDD) and the number of growing days (NGD). The GDD were defined as follows:

After Dupuis and Hann (2009), GDD were calculated as follows:

$$GDD(t) = \sum_{i=t_0}^{t} max\{0, (T_i - T_{base}) \cdot \Delta t\} \quad (1)$$

where t is the time (here in days) with t_0 the reference day to start the calculation, Δt is the time step (equal to 1 day), T_i is the daily average of the modeled surface water temperature of day i and T_{base} is a physiological threshold below which growth does not occur. [...] As in Dupuis and Hann (2009), the value of 4°C was selected for T_{base}. Such value was chosen to be a representative baseline for the growth of the whole phytoplankton community in Lake Champs-sur-Marne, generally composed of cyanobacteria, green algae and diatoms.

While for the NGD:

The number of growing days (NGD) at day t is defined as the number of days during which $(T_i - T_{base}) > 0$ from day $i = t_0$ to $i = t$. It represents a proxy for the duration of the period favorable to growth for the phytoplankton community.

The main remarks done by the Reviewers regarded the choice of such a low value for the base temperature and in general the relevance of the NGD in relation to biomass production. Furthermore, also the lack of an upper limit for the GDD that takes into account reduced phytoplankton growth under high temperature was pointed out.

According to these remarks, in the revised version the indices related to primary production were changed. We focus our attention only on cyanobacteria, and not on the whole phytoplankton community present in the study site. The NGD are completely abandoned, while an upper limit for cyanobacteria growth is added for the GDD. Furthermore, the concept of thermal growth rate (GR) is introduced. This allows to thoroughly address the effect of water temperature on potential cyanobacteria production, while taking into account growth reduction at low or extremely high temperatures.

The definition of the new indices (GR and GDD) is now as follows:

Under the assumption of nutrient and light availability, phytoplankton growth rate can be modelled, for different species, as a function of temperature as follows (Bernard and Rémond, 2012) :

$$k(T) = k_{opt}\frac{(T-T_{max})(T-T_{min})^2}{(T_{opt}-T_{min})[(T_{opt}-T_{min})(T-T_{opt})-(T_{opt}-T_{max}(T_{opt}+T_{min}-2T))]},\ \forall\, T \in [T_{min}, T_{max}] \tag{2}$$

where k$_{opt}$ is the optimal growth rate, T_{min} the minimal temperature, T$_{opt}$ the optimal temperature and T_{max} the maximal temperature. The model parameters were calibrated by You et al. (2018) through experimental data to describe the response to water temperature of *Microcystis aeruginosa*, a species of cyanobacteria present in Lake Champs-sur-Marne and often dominant in freshwater bodies globally. The same values are used in this work:

$$k_{opt} = 0.74\mathrm{d}^{-1},\ T_{min} = 0°C,\ T_{opt} = 27.5°C,\ T_{max} = 38.4°C. \tag{3}$$

Microcystis aeruginosa is thought to be favored by the warmer water temperatures induced by climate change. However, the curve obtained from eq. 2 and 3 (shown in figure 1), is here more generally intended to be representative of the typical thermal response of cyanobacteria with high optimum temperature. Mean annual and seasonal (according to 2.3) growth rates are calculated through eq. 2 using simulated surface water temperature, and analysed over space and time.

The growing degree days are a weather based indicator for biological growth, widely used in the field of agronomy. Based on air temperature, it gives an estimate of the rate of development and of the span of the growing season for terrestrial plants and insects. It is a useful indicator capable to link global warming and biology (Grigorieva et al., 2010; Schlenker et al., 2007). Approaches based on GDD have been increasingly applied to phytoplankton communities and fisheries (e.g. Gillooly, 2000; Neuheimer and Taggart, 2007; Ralston et al., 2014; Dupuis and Hann, 2009), in order to correlate water temperature and phytoplankton growth while taking into account interannual variability. After Dupuis and Hann (2009), GDD were calculated as follows:

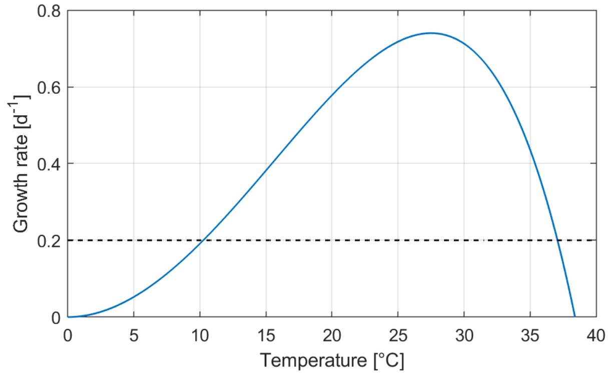

Figure 1. Thermal growth rate calculated after equation 2. The horizontal dashed line for GR=0.2 d^{-1} meets the curve at the temperature limits for the calculation of the GDD (10°c and 37°C, respectively).

$$GDD(t) = \sum_{i=t_0}^{t} a_i \cdot (T_i - T_{base}) \cdot \Delta t, \quad \text{with } a_i = \begin{cases} 1 & \text{if } T_{base} < T_i < T_{sup} \\ 0 & \text{elsewhere} \end{cases} \tag{4}$$

where t is the time (here in days) with t_0 the reference day to start the calculation, Δt is the time step (equal to 1 day), T_i is the daily average of the modeled surface water temperature of day i and T_{base} (respectively T_{sup}) is a physiological threshold below which (respectively above which) growth does not occur. Compared to the formulation found in Dupuis and Hann (2009), an upper limit for growth was introduced here (T_{sup}) to take into account high temperature stress. Our focus here is, as for the GR, on cyanobacteria. After Thomas et al. (2016) and based on the latitude of the study site, we set the base temperature at 10°C and the upper limit for growth at 37°C. This results in considering, for the cacluation of the GDD, only temperatures that yield to a GR above 0.2 d^{-1} (see figure 1).

GDD can be calculated on an annual or a seasonal basis by adjusting the values of t_0 and t. Annual GDD are calculated from the first of January until the 31st of December. Seasonal GDD are obtained according to the definitions of section 2.3.

3D analysis

In the revised version, the spatial analysis is not limited to the stratification dynamics but encompasses also the distribution of surface water temperature, thermal growth rate and growing degree days. Furthermore, a more structured study of the spatial heterogeneity is proposed. Its main focus is on the distribution of stratification and surface water temperature and on their impact on potential cyanobacteria production. The horizontal distribution of the variables under examination is fitted to a non parametric probability density function (the Kernel function) and finally plotted as a heat map.

Following is its description as in the revised version. The related paragraphs in the results and discussion sections were changed according to this new methodology and can be found in the revised manuscript.

The long-term evolution and the spatial variability of the thermal regime of Lake Champs-sur-Marne was further analysed exploiting the three-dimensional model simulations. Mean annual surface water temperature, annual SSD, mean annual GR and annual GDD were computed on the whole computational domain, with the objective of investigating the relation between climate change and time evolution of the spatial distribution of these variables. For each variable x, the overall mean annual value x_m (averaged over the complete domain) and the deviation from the mean value $(x - x_m)$ have then been computed. In order to quantify the spatial heterogeneity of these variables, the probability distribution of the deviation from the mean value of each variable was finally calculated on the computational domain and fitted, for each year, with a non-parametric Kernel probability distribution through the Matlab *pdf* function. The resulting probability density function (PDF) was plotted over time as a heat map and the mean value as a simple line plot. This allows to visualize both the time and the spatial evolution of the variable under consideration, by looking at the mean value and at the range of values characterized by a non-zero probability.

During stably stratified periods, cyanobacteria are favored over other algal groups because of their ability to move within the water column and possibly float towards the water surface (Humphries and Lyne, 1988; Wagner and Adrian, 2009; You et al., 2018). For this reason, the spatial analysis of the GR and GDD was completed, by calculating these two indices only on stable stratified days during each year. The obtained GR were further averaged for each cell over the local number of stably stratified days. Cells that showed an annual number of SSD<10 where discarded from this analysis. Finally, the resulting modified indices were analysed over space and time as described above by using a non-parametric Kernel probability distribution as an approximation of the PDF for each simulated year.

Additional modifications

According to the suggestions found in the reviews other additional modifications were done to our text. They didn't entail major changes to the text, but are listed hereafter.

- The process and the results of validation were more clearly explained, especially through additional figures showing more in detail the model performances in terms of water temperature (parity diagrams between simulation and observations were added) and stratification dynamics (with a visual comparison of the observed and simulated stratification events).

- In order to further characterize the dynamics of the stratification in a polymictic water body, besides the calculation of the stably stratified days (SSD) and the Schmidt stability index, also the annual frequency of stable stratification events and the duration of the longest consecutive stratification event were analyzed.

- The title of the article was slightly changed from "The response of small and shallow lakes to climate change: new insights from hindcast modelling", to: "The thermal response of small and shallow lakes to climate change: new insights from 3D hindcast modelling".

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