Modelling of the shallow lake response to climate variability

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1 Introduction

Physical processes of heat and mass exchange are of great importance for lake ecosystems and incorporate, at the same time, a lot of feedbacks that makes it difficult to uncover the response of lakes to climatic changes. Existing climatic trends call for elaboration of criteria relating the seasonal stratification regime to the external conditions variability. Some of small lakes are stratified continuously during the summer heating period as long as surface temperatures are higher than 4°C (so-called *dimictic* lakes), other become full-mixed repeatedly during the summer on account of winds and convection, i.e. have the *polymictic* character. Climatic changes in the atmospheric influence can potentially lead to switching between the regimes in a certain lake that will alternate all interactions within the lake's ecosystem and, possibly, completely replace an existing ecosystem by another one. Answering the question about the lake regime dependence on external forcing needs adequate description of the process of turbulent mixing in stratified fluids. Existing methods of its description are based on introducing of different degree of empiricism into the problem. Even the probably most developed and widely used in applications two-equation turbulence models (so-called k-ε and Mellor-Yamada level 2.5 models) do not offer a universal scheme of accounting of non-local mixing in stratified media. At the same time, these models are complicated enough mathematically that makes application of such a model to a large number of lakes on climatic scales a time-consuming task with questionable results. Implementation of a parameterised bulk model based on the hypothesis of self-similarity of the thermocline is considered below as the physically sound and computationally efficient alternative for using in climatic studies. The vertical density structure of a lake can be represented in a bulk manner as having two-layered structure with a well-mixed upper layer. In order to obtain a reasonable compromise between physical realism and computational economy, the concept of self-similarity of the temperature profile in the thermocline can be applied to the stratified layer below the upper mixed layer. The concept was put forward by [Kitaigorodski and Miropolski, 1970] and implies that the dimensionless temperature profile in the thermocline can be fairly accurately parameterised through a “universal” function of dimensionless depth, where the temperature difference across the thermocline and its thickness are used as relevant scaling parameters (Fig. 1). The idea has received further support through the observational studies [Mälkki and Tamsalu, 1985]. A plausible theoretical explanation for the observed self-similarity was offered in case of deepening of the upper mixed layer [Turner, 1978; Kirillin, 2002]. A number of computationally-efficient parameterised models have been developed based on the self-similar representation of the temperature profile and successfully applied to simulate the seasonal thermocline in the ocean [Filyushkin and Miropol'skij, 1981] and the rise of the inversion capping convectively mixed layer in the atmosphere [Deardorff, 1979; Fedorovich and Mironov, 1995].

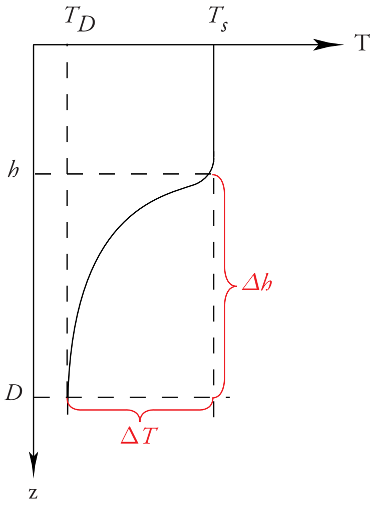

Figure 1: The model representation of the vertical temperature profile in a lake. Here, T_S is the mixed layer temperature, T_D is the temperature at lake's bottom, and h is the mixed layer depth. Dimensionless co-ordinates are build as $\zeta = (z\text{-}h)/\Delta h$, $\vartheta = [T(z)\text{-}T_D]/\Delta T$. The function $\vartheta(\zeta)$ is assumed to have a quasi-universal character in all lakes.

2 Materials and methods

The concept of the thermocline self-similarity is used in the model `TeMix` of the seasonal cycle of temperature and mixing in freshwater lakes [Mironov et al., 1991]. The model makes use of the two-layer parametric representation of the vertical temperature structure. The upper layer is treated as well-mixed and vertically homogeneous. The structure of the lower stably-stratified layer, the lake thermocline, is parameterised using a polynomial self-similar representation of the temperature profile $\vartheta(\zeta)$ (see Fig. 1). After integrating of the original partial differential equations of heat and energy transfer over each layer the problem diminishes to a system of ordinary differential equations describing evolution of parameters T_S, T_D and h. The mixed layer depth h is computed from the prognostic entrainment equation for convective mixed layer deepening, and from the diagnostic equilibrium boundary-layer depth formulation in conditions of wind mixing against the stabilising surface buoyancy flux. In this sense, the model belongs to the family of bulk models. The distinguishing feature of the present model is the fully parameterised representation of the vertical temperature profile that results in robust and computationally efficient algorithm, avoiding usage of purely known “constants” and conserving physical soundness. In previous studies, the model `TeMix` was successfully applied to simulation of thermal regime of Lakes Ladoga and Sevan as well as of small Karelian lakes in North-Western Russia. Here, we test the model on observational data from shallow Lake Müggelsee, located in Berlin, Germany. Prognostic calculations of the temperature variability in the lake have been performed for the next 55 years based on climatic scenarios of the Potsdam Institute for Climate Impact Research (PIK). Short analysis of the modelled shallow lake response to climatic changes is given below.

3 Results and discussion

3.1 Model validation

The model validation was performed on 17 years observational data from shallow polymictic Lake Müggelsee [Kirillin, 2001; Kirillin, 2002]. The model performance was also compared with results of k-ε modelling for the same lake (Fig. 2).

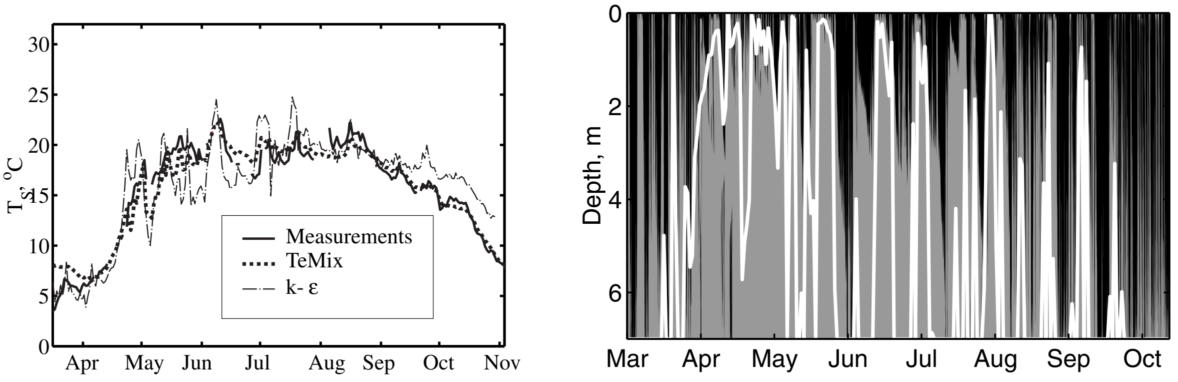

Figure 2: Examples of lake temperature and stratification calculation. Lake Müggelsee, 1993. Left: Surface temperature evolution observed in the lake (solid line), that predicted by `TeMix` (dotted line) and by the k-ε model (dash-dotted line). Right: Mixed layer depth calculated with `TeMix` (white line) versus regions of strong mixing (TKE ≥ 10^{-5} m^2/s^2) predicted by k-ε model (black filled areas).

The numerical code for k-ε modelling was used, developed by the GOTM project team [Burchard et al.]. The model `TeMix` has demonstrated good abilities in reproduction of the temperature evolution in the lake as well as in prediction of the mixed layer depth and in modelling the polymictic behaviour of the lake. The values of model parameters T_S, T_D and h are in good agreement with those observed in Lake Müggelsee and are close to results of k-ε modelling, being achieved at essentially lower computational costs. It makes the model an attractive tool for climate-related studies, where series of long-term calculations for various external conditions are required.

3.2 Model simulations with climatic scenarios

Modelling of Lake Müggelsee response to the expected climatic changes in the next half-century was performed using atmospheric forcing from regional climatic scenarios for River Elbe basin. The scenarios were developed by the Potsdam Institute for Climate Impact Research (PIK) in frames of the "GLOWA-Elbe" project (Integrated Analysis of the Impacts of the Environment and Society in the Elbe River Basin). They include 100 climatic realizations with daily averaged meteorological values (solar radiation, air temperature, wind, air humidity etc.) covering the time span 2001-2055. Direct usage of these values in the model input has allowed distinguishing some trends in the temperature and mixing regime of the lake, related to climate changes (Fig. 3). In the figure, modelling results are shown for one of the typical climatic scenarios. The yearly averaged water temperatures increase on about 1.5°C in 50 years that coincides with increasing in the mean air temperature (1.4°C) envisaged in the scenario. It is the consequent result of the polymictic character of Lake Müggelsee: on sufficiently large time scales, the lake can be considered as a completely mixed water body, reacting instantaneously to the air temperature variations. More complicated, time-delayed response should be expected in dimictic lakes, where meteorological conditions during the short periods of spring and autumn overturns determine to a great extend the heat storage in a lake during the whole year.

Another noteworthy result consists in the shift of the summer temperature maximum to later dates. The model predicts the lag about one month (from mid-July to mid-August) through the calculation period. It results also in essentially higher autumn water temperatures and shorter icecovered periods, whereas the temperature dynamics during the spring and the early summer does not change significantly. Such an alteration in the seasonal temperature cycle can impact biological communities in a lake and should be taken into account when considering ecological interactions in climatic context.

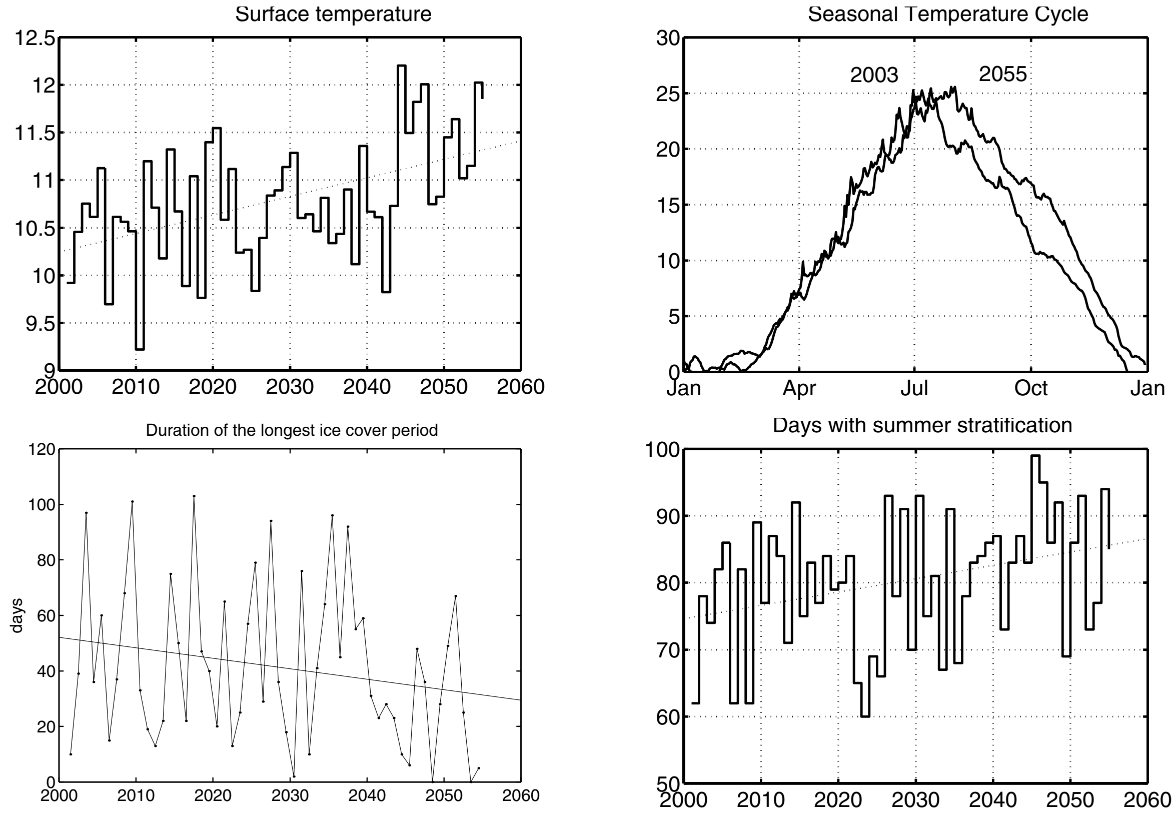

Figure 3: Examples of lake temperature and stratification calculation with meteorology input from a PIK climatic scenario. Lake Müggelsee, 2001-2055. From left-top to right-bottom: yearly averaged surface temperature evolution; seasonal temperature cycle in 2003 and 2055; duration of the longest ice cover period in year; number of days with vertical temperature stratification occurrence in summer.

The overall effect of the expected climatic changes on the vertical mixing regime consists in increased number of stratification events in the lake. The period of vertical stratification in the lake is about 20% longer in 2055 than in the beginning of calculations. It can be expected that the same climatic scenario can lead to switching from polymictic to dimictic regime in a certain lake, which would differ in morphometry or geographical location from that, modelled here.

4 Conclusions

Bulk modelling of thermal regime in a lake based on the concept of thermocline self-similarity gives reliable results at low computational costs and represents an attractive tool for lake-related environmental applications. This conclusion is also approved by comparison of the model performance with that of the k-ε model and by model tests on observations in a shallow polymictic lake. Model calculations with meteorological input from climatic scenarios show, in addition to the mean temperature increase, a time shift in seasonal temperature cycle and decreasing of the vertical mixing intensity in summer. The results are of great importance for analysis of the lake ecosystem response to the climate variability. The modelled changes in the mixing intensity imply a possibility of mixing regime transition in a lake from polymictic to the dimictic one. Oncoming research should uncover the conditions of such a transition including meteorological forcing and the lake morphometry. A comprehensive study of climatic variations in lakes stipulates incorporation of the heat exchange with lake sediments and of the realistic model for ice dynamics into the model algorithm.

Acknowledgements

This study was partially founded by the German Ministry of Education and Research within the Project GLOWA-Elbe ``Integral analysis of the consequences of global change on the environment and the society within the Elbe catchment". Useful contacts with the EU-Project INTAS-2132 ``Representation of lakes in numerical models for environmental applications" are gratefully acknowledged.

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