First publ. in: Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 30 (2009), Part 5, pp. 701–704

Simulating phytoplankton community dynamics in Lake Constance with a coupled hydrodynamic-ecological model

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Introduction

Lake Constance is among the largest lakes in central Europe and represents the most important drinking water reservoir in southwestern Germany. About 4 million people depend on this lake for their drinking water supply, and considerable efforts have been made to protect its high water quality (Stabel 1998). In addition to a drinking water supply, the lake is the receiving water body of numerous waste-water plants within its catchment and is moreover used for recreational purposes and fisheries. To improve water quality management of the lake, a research project (see www.bodenseeonline.de) was initiated to develop a model-based decision support system. The model system consists of a coupled hydrodynamic ecological model that can be either run in a 1D-setting (DYRESM-CAEDYM) or a 3D setting (ELCOM-CAEDYM). The establishment of the model systems requires the adaptation of the ecological model CAEDYM to Lake Constance, achieved by long-term simulations and comparison to historical data. The main goal of this study is to adapt the ecological model to reflect the physiological properties of the planktonic community, particularly for phytoplankton, which shows a great functional diversity. This diversity needs to be taken into account (Reynolds et al. 2002, Sommer et al. 1986) for phytoplankton succession to be represented properly.

Key words: DYRESM-CAEDYM, functional phytoplankton groups, hydrodynamics, large lakes, water quality model

Study site

Lake Constance is situated on the northern edge of the central European Alps along the borders of Germany, Switzerland, and Austria. With a surface area of 473 km^2, an average depth of 100 m, and a maximal depth of 254 m, Lake Constance is among the largest and deepest lakes in Europe. The lake suffered from eutrophication between 1960 and 1980 and has since undergone intensive reoligotrophication. Detailed description of the study site and the history of the lake are given elsewhere (Bäuerle et al. 1998, Güde et al. 1998, Wessels 1998).

Material and methods

Simulations were performed with the coupled hydrodynamic ecological model DYRESM-CAEDYM. Details of the hydrodynamic model DYRESM can be derived from Gal et al. (2003) and Yeates & Imberger (2003). A description of the ecological model CAEDYM is given in Bruce et al. (2006) and Hipsey et al. (2006). Parameterisation of the models is provided by the first author upon request. We used 1995–1997 as an intensive study period because good estimates of external nutrient inputs were available. A long-term simulation from 1979–2000 was calculated with partly interpolated data for external inputs.

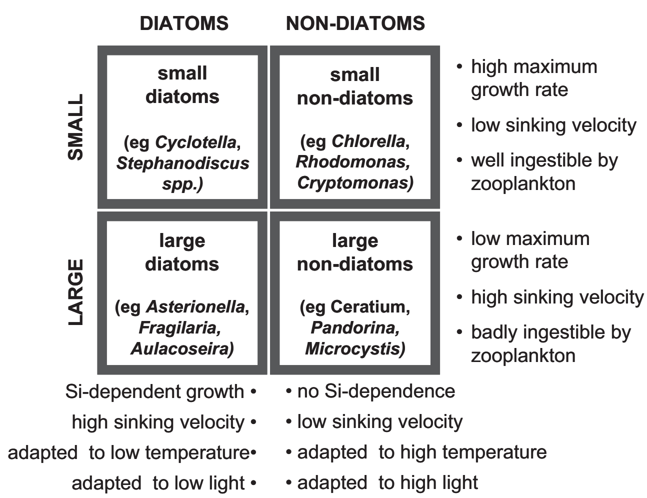

Fig. 1. Within the ecological model the functional classification of the phytoplankton was realised by a simple 2 × 2 matrix. Taxonomic characteristics (diatom/non-diatom) and cell size (large/small) were associated with specific physiological properties (next to boxes).

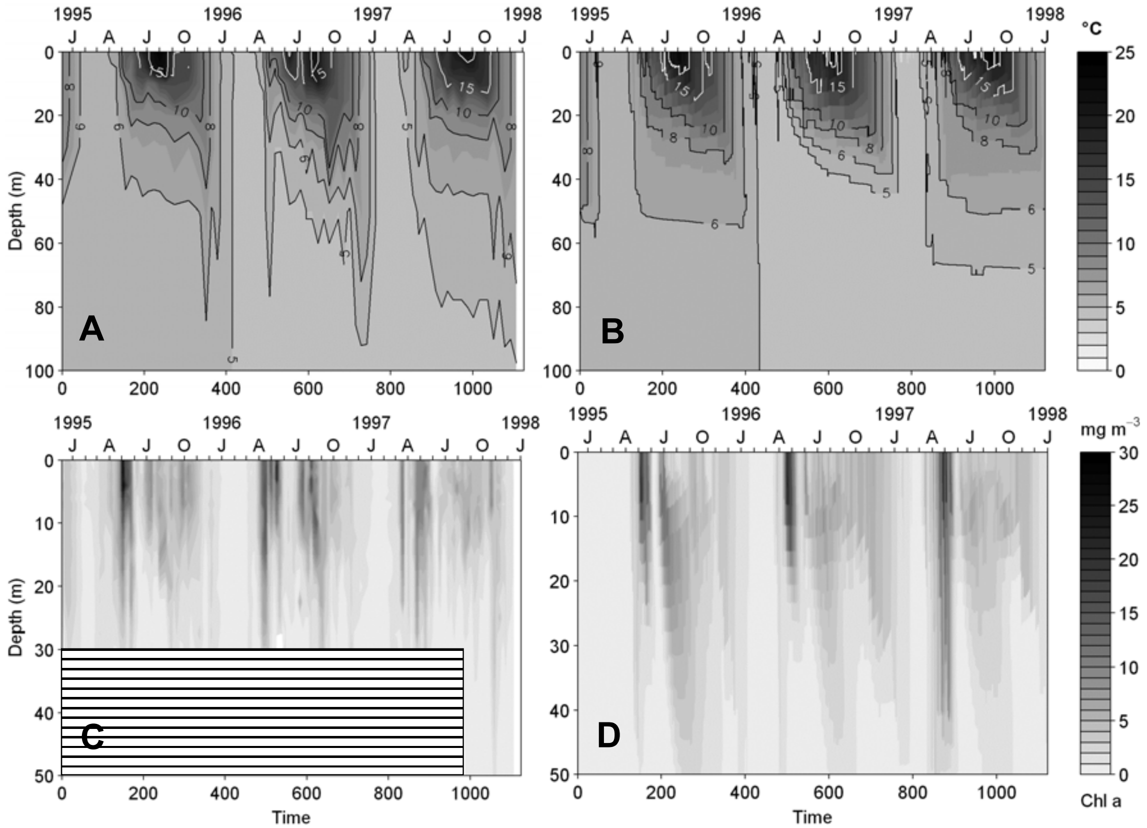

Fig. 2. Comparison of measured data and simulation results for 1995–1997 in Lake Constance; (A) measured temperature, (B) simulated temperature, (C) measured total Chlorophyll a, striped area = no data available (D) simulated chlorophyll. In the temperature plots contour lines were added at 5, 6, 8, 10, 15, and 20 °C.

The phytoplankton community in the model was represented by 4 functional groups that differ systematically in their physiological properties (Fig. 1). Parameters were retrieved from the literature. Long-term data of temperature and chlorophyll in Lake Constance were provided by the long-term monitoring program of Lake Constance conducted by the Limnological Institute of the University of Konstanz (Bäuerle et al. 1998, Häse et al. 1998, unpubl. data). Data acquisition was performed within the Special Collaborative Program (SFB) 248 "Cycling of Matter in Lake Constance," supported by the Deutsche Forschungsgemeinschaft (DFG). Long-term data of phytoplankton biovolume were provided by the Internationale Gewässerschutzkommission für den Bodensee (IGKB).

Results and discussion

The results from the hydrodynamic model for 1995–1997 displayed the annual cycle of stratification and winter mixing typical for Lake Constance (Fig. 2A). Comparison of simulated water temperatures with temperature measurements in the lake revealed close agreement between both, resulting in a high coefficient of determination ($r^2 = 0.96$; Fig. 2A and 2B). Large deviations between simulated and measured temperature were mainly restricted to the thermocline, where internal waves led to high spatiotemporal variability in the temperature measurements (Bäuerle et al. 1998).

The ecological model was able to reproduce the characteristic patterns in the annual dynamics of total chlorophyll (Fig. 2C and 2D). The spring phytoplankton bloom started simultaneously with the onset of stratification and consisted mainly of small diatoms and, to a lesser extent, small non-diatoms, which corresponded to empirical observations in Lake Constance (Sommer et al. 1986). During the clear water phase, the intense zooplankton grazing led to a shift toward larger algae, which in 1995–1997 almost completely consisted of large diatoms. Because these algae are characterised by rather high sinking velocities, chlorophyll was distributed into greater depths and displayed a maximum between 10 and 20 m depth. Due to the depletion of dissolved phosphate by phytoplankton growth and sedimentation over the season, chlorophyll concentrations were lower during the summer than during the spring bloom. In addition, reduced

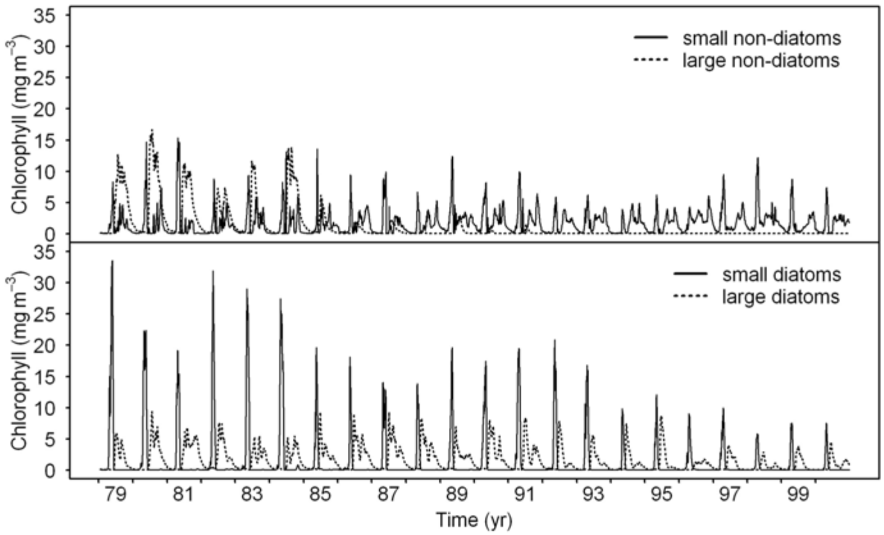

Fig. 3. Simulated long-term dynamics (1979–2000) of the functional phytoplankton groups (average from 0–20m). Note that the 2 non-diatom groups are depicted in the upper panel and the 2 diatom groups in the lower panel.

light availability at those depths where summer phytoplankton resides may have also contributed to this reduction in chlorophyll concentration during summer.

In a long-term simulation from 1979–2000 the reaction of the model to the reoligotrophication was simulated (Fig. 3). Within this period, the total annual dissolved phosphorus load of Lake Constance declined from approximately 900 tons per year to about 200. The lake's reaction to this nutrient reduction was delayed, attributed to the large volume of the lake and the average residence time of about 5 years. Reduction of chlorophyll was not parallel to the phosphorus load reduction, but rather occurred stepwise in the first half of the 1990s. Chlorophyll concentrations declined stronger during summer where nutrient limitation became more pronounced during reoligotrophication. Corresponding observations by Gaedke (1998) were reported for the summer chlorophyll concentrations. In the model outputs this reduction in summer chlorophyll was also associated with a shift from large non-diatoms to large diatoms, which are better competitors for phosphorus (Reynolds et al. 2002). Over the whole reoligotrophication period, a rather constant annual pattern of abundance was found for the small non-diatoms. In Lake Constance, this group is predominantly represented by cryptophytes.

Based on yearly averaged chlorophyll concentrations, the long-term response of the simulated phytoplankton community seems to parallel observations of total phytoplankton biovolume in the lake (Fig. 4). The simulated chlorophyll concentrations show a stepwise reaction to the reoligotrophication. These abrupt decreases in simulated phytoplankton are associated with sudden changes in the functional composition of the community (e.g., the obvious decrease in the abundance of large non-diatoms between 1984 and 1985). These algae are considered to be functionally adapted to eutrophic conditions; however, larger deviations between simulations and measurements occurred in single years (e.g., 1988; Fig. 4); how such high standing stocks of phytoplankton have been prevalent despite constantly decreasing nutrient concentrations remains unexplained.

The coupled model system DYRESM-CAEDYM has already been applied to simulate hydrodynamics and plankton succession in Lake Kinneret, Israel (Bruce et al. 2006). However, because the structure of CAEDYM is strongly modularised allowing different levels of model complexity, and because the choice of an appropriate model structure remains entirely to the user, the applications are not comparable. The Kinneret study was focused on nutrient recycling by zooplankton, whereas our application concentrated on functional phytoplankton

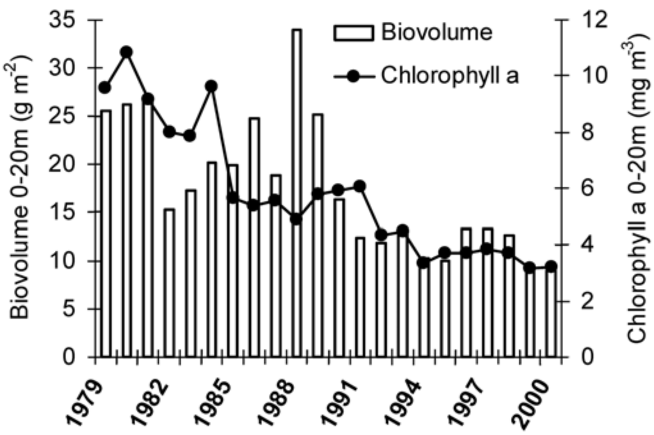

Fig. 4. Yearly average of measured areal (0–20m) phytoplankton biovolume (bars) and yearly averaged simulated chlorophyll a concentrations in the upper 20 m of Lake Constance (line).

succession and trophic change. In conclusion, the configuration and parameterisation of CAEDYM appears promising and undoubtedly applicable to the pelagic zone of Lake Constance.

Acknowledgements

We thank the Internationale Gewässerschutzkommission für den Bodensee, the Institut für Seenforschung, and the Limnological Institute for providing data. We are also grateful to the colleagues from the BodenseeOnline-project for their support. Financial support was provided by Deutsche Forschungsgemeinschaft under grant Ro 1008/11-1 and within the priority program 1162 “AQUASHIFT” (Pe 701/2-2) as well as by the German-Israeli Young Scientists Exchange Program under grant FZK0501/YSEP19.

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