Characterization of deep water renewal in Lake Baikal: a numerical analysis

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Lake Baikal; deep ventilation; downwelling; thermobaricity; one-dimensional model.

EXTENDED ABSTRACT

Introduction
With a volume of 23‘615 km$^3$ and a maximum depth of 1‘642 m, Lake Baikal (Southern Siberia, see Figure 1) is the largest and deepest freshwater basin on Earth. Due to its huge depth, only the upper layer of the lake (approximately 250 m) follows the typical mixing dynamics of temperate lakes. Complete overturn in this layer occurs twice a year, in late May/early June and late December/early January, when surface water temperature approaches the mesothermal temperature maximum (i.e., the temperature where the temperature profile meets the temperature of maximum density). Differently, the hypolimnion is only occasionally subjected to a partial renewal of its waters, as a consequence of periodical deep downwelling events that are responsible for the displacements of water volumes from the surface down to the abyss of the lake. Direct observations (e.g., Weiss et al., 1991) showed that the key mechanism triggering deep downwellings is represented by the onset of buoyancy-driven instabilities, which are mutually controlled by thermobaricity (i.e., the combined dependence of water density on temperature and pressure) and external forcing (mainly wind). Despite deep downwellings have been widely observed in Lake Baikal, large uncertainty still exists with respect to their precise description and quantification.

Materials and methods
Seasonal and episodic convective mixing in Lake Baikal has been investigated here by means of a simplified one-dimensional model recently proposed by Piccolroaz and Toffolon (2013). Three main algorithms are at the basis of the model: a reaction-diffusion equation for temperature and other tracers (e.g. dissolved oxygen), and two Lagrangian algorithms, the
first to handle buoyancy-driven convection due to density instability (including thermobaric effects) and the other to reproduce the deep downwelling mechanism.

Results and discussion

The calibration of the parameters has been obtained by performing a medium-term simulation over a historical period (40 years, from 1958 to 1998), for which measured temperature (courtesy of prof. A. Wüest), CFC-12 and dissolved oxygen profiles were available. Additionally, a long-term 1000-year simulation has been run by maintaining current climate conditions unchanged, which provided an indirect validation of the model. In both cases, numerical results have been shown to be in good agreement with observed data (see Figure 2), suggesting the suitability and robustness of the core algorithms and, in general, a proper performance of the model.

The analysis of the results obtained from the long term simulation allowed for a detailed description of the mixing regime and thermal dynamics of the lake (e.g. seasonality of temperature and diffusivity profiles), and a statistical characterization of deep ventilation, which mainly concerns: timing, typical volumes and temperatures, energy balance and vertical distribution of downwelling volumes. In particular, deep downwellings have been estimated to have a mean annual sinking volume of $91.6\pm73.0$ km$^3$ and a mean annual temperature of $3.27\pm0.06^\circ$C. Concerning the vertical distribution of sinking volumes, nearly the 26% of deep downwelling have been found to reach depth greater than 1300 m, whereas the remaining percentage is mainly distributed between 150 and 900 m, with a peak at about 200-250 m that is due to the numerous shallow and relatively warm events that occur as soon as the water column approaches a nearly homogeneous temperature. Finally, results suggest a strong seasonality of the downwelling events. In this respect, some interesting insights can be raised about the role that the seasonal evolution of thermal conditions of the lake (e.g. thickness of the surface well-mixed layer, strength of the thermal stratification, depth of the mesothermal maximum) plays on the occurrence of deep water renewal.

**Figure 2.** Comparison between the mean annual cycles of observed (left) and modelled (right) vertical temperature profiles (RMSE=0.07°C, Mean Absolute Error=0.03°C and Maximum Absolute Error=0.78°C).

REFERENCES
