Explaining water temperature changes in Lake Superior by means of a simple lumped model

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Lake Superior; water temperature; air temperature; climate change; heat budget.

EXTENDED ABSTRACT

Introduction

A significant warming has been noticed in the Great Lakes region during the last decades. One of the peculiar aspects is that water temperature in summer warmed up more rapidly than air temperature (+0.15 °C yr^{-1} and +0.09 °C yr^{-1}, respectively, see Figure 1), based on measurements collected by several monitoring buoys and coastal stations in the period 1985-2011 (data from NOAA). Particularly interesting is the extraordinary summer warming that affected Lake Superior in 1998, which can be seen as an exceptional example of the amplified response of the lake system to increasingly warmer atmospheric conditions. This event is analysed by means of the recently developed lumped model *air2water* (Piccolroaz et al., 2013), which allows for simulating and predicting surface water temperature as a function of air temperature only. An explanation of the phenomenon is given based on the positive feedback with the stratification regime of the lake.

Materials and methods

In spite of the simple formulation and the limited number of parameters (from 4 to 8 for different versions), the *air2water* model is able to satisfactorily capture the seasonal variations and the inter-annual dynamics in surface water temperature of lakes, thus representing a tool for both conceptual studies and real case analyses. The fact that the model is data-driven, while being based on physical grounds, allows for the direct acquisition of information about the studied system in the calibration phase, which is performed through a Monte Carlo approach. The model in its 8-parameter version (from a_1 to a_8) reads as follows:

$$\frac{dT_w}{dt} = \frac{1}{\delta}\left\{a_1 + a_2 T_a - a_3 T_w + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\}, \qquad (1)$$

$$\begin{cases} \delta = \exp\left(-\dfrac{T_w - T_h}{a_4}\right) & \text{for} \quad T_w \geq T_h \\ \delta = \exp\left(-\dfrac{T_h - T_w}{a_7}\right) + \exp\left(-\dfrac{T_w}{a_8}\right) & \text{for} \quad T_w < T_h \end{cases}, \qquad (2)$$

where T_w is water temperature, T_a is air temperature, δ is a dimensionless number related with the depth of the surface volume affected by the heat exchange with the atmosphere, and T_h is a reference value of the deep water temperature (approximately 4 °C for dimictic lakes).

Results and discussion

The application of the model to Lake Superior suggests that the unusual water warming in summer 1998 can be explained by means of two combined factors: the extremely high air temperature and the increased strength of the stratification, which reduces the volume that effectively concurs to the variation of the surface water temperature (i.e., the parameter δ) because of the reduction of the heat fluxes across the thermocline. Figure 2 shows an application of the model to two years (1997 and 1998): air temperature in 1998 is always higher than in 1997, but the abrupt change of slope in water temperature trend occurring at the end of June 1998 is mainly due to the strong decrease of δ, which corresponds to a more isolated epilimnion and hence to a more intense warming of surface water. Conversely, in 1997, the decrease of δ occurs later, when air temperature has almost ceased to grow.

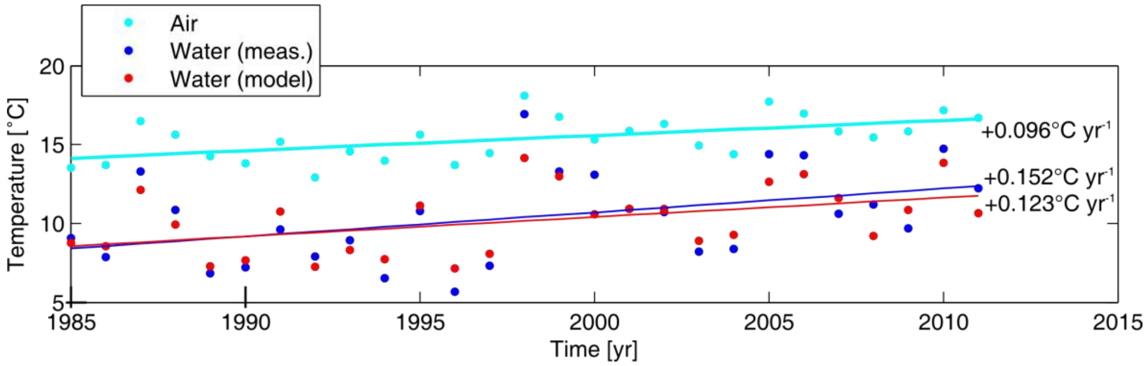

Figure 1. Long-term trends of summer average air and water temperatures within the period 1985-2011: observations of air and water temperatures, and modelled water temperature.

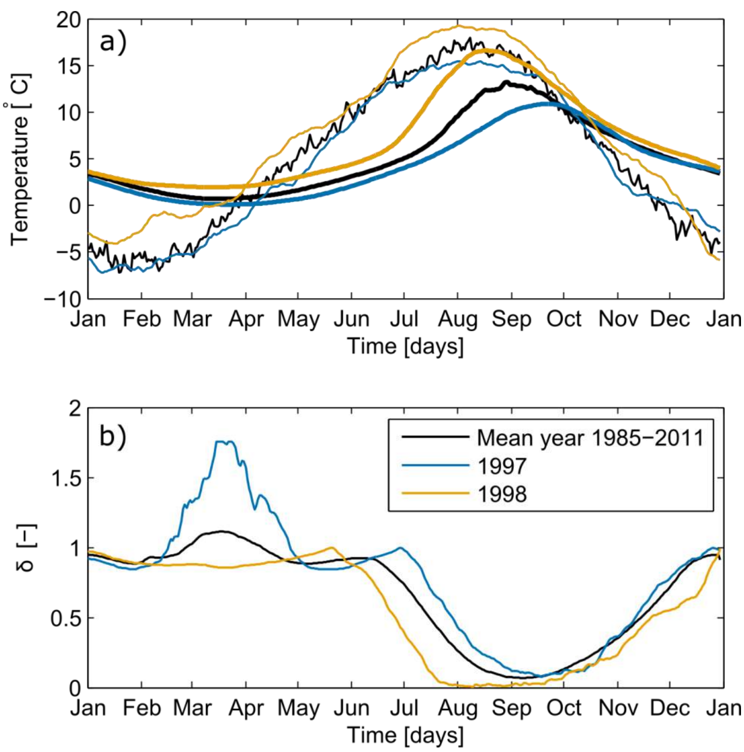

Figure 2. Comparison between the annual cycles of: a) measured air temperature (thin lines, smoothed for sake of clarity) and simulated water temperature (thick lines), and b) the dimensionless parameter δ, for the mean year (1985-2011) and the two years 1997 and 1998.

REFERENCES

Piccolroaz, S., M. Toffolon, and B. Majone (2013), A simple lumped model to convert air temperature into surface water temperature in lakes, *Hydrol. Earth Syst. Sci.*, **17**, 3323-3338, doi:10.5194/hess-17-3323-2013.