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Thermobaric stratification and circulation in very deep freshwater lakes

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Deep lakes; thermobaricity, compressibility, water density, physical limnology

ABSTRACT

Themobaricity, i.e. temperature dependence of compressibility (of pure water)

$$0 \neq \frac{\partial \rho_{in-situ}}{\partial T \partial p} = \frac{\partial}{\partial T}\left(\frac{\partial \rho_{in-situ}}{\partial p}\right),$$

leads to a shift of the temperature of maximum density by 0.02 °C/bar. This results not simply in a shift of temperatures in the deep waters, but also controls the deep recirculation in sufficiently deep lakes. This effect has been studied in Lake Baikal (e.g. Weiss 1991), but investigations in other lakes are rare (e.g. Crawford and Collier, 1997), although about half of the deep lakes are located in a climate where the thermobaric stratification is relevant. We distinguish two classes, i.e. horizontally homogeneous lakes and lakes with horizontal gradients. We demonstrate, how deep water recirculation is inhibited or accomplished.

The temperature of maximum density for pure water can be drawn as a profile against depth $T_{md}(z)$. It starts at 4°C at the surface and reaches about 3.0°C at the base of a 500m deep lake. We present a simplistic model of a very deep pure water lake: surface temperatures are controlled by a user, while the model checks stability of the water column and does the required mixing, whenever instabilities occur. Forcing low surface temperatures through a model winter, the model reveals an asymmetry between autumn and spring recirculation. A period of homogeneous water temperature does not exist as in lakes not affected by thermobaricity. Over the winter period, the water column becomes subdivided into two layers that never completely mix with each other. No water property is separating both layers; this is accomplished by thermobaricity, as will be shown: the upper layer is directly affected by atmospheric heat transfer and presents itself for a large portion of the winter “inversely” temperature stratified. The intersection with the profile of T_{md} marks the separation to the lower layer, which is continuously convectively mixing driven by a heat flux to the upper layer. After spring, the lake remains with a quasi homogeneous deep layer, a layer that follows the Tmd profile and a thin surface layer, which follows the atmospheric temperature forcing. We compare the model results with measureemnts from Lake Shikotsu, Japan (Boehrer et al. 2008).

The picture is different, if horizontal gradients are permitted. We show measurements taken in five Norwegian fjord lakes early at a time when the lakes have just started into the summer stratification. All lakes were deeper than 200m. We measured profiles of temperature, electrical conductivity, dissolved oxygen and pH. Results confirm the thermobaric stratification, i.e. temperatures in the deeper waters lie below 4°C even during the summer stratification period (see Fig. 1). The temperature gradient in the lakes Mjøsa, Tinnsjø and Tyrifjord corresponds to

$$\frac{\partial T}{\partial z} = 0.6\frac{\partial T_{md}}{\partial z},$$

which is close to a stability criterion promoted by Eklund in 1965. A closer check of the conditions indicate that the Eklund criterion does not apply in these conditions, and in deed, two lakes (Hornindalsvatn and Breimsvatn) oppose the stability criterion (Figure 1).

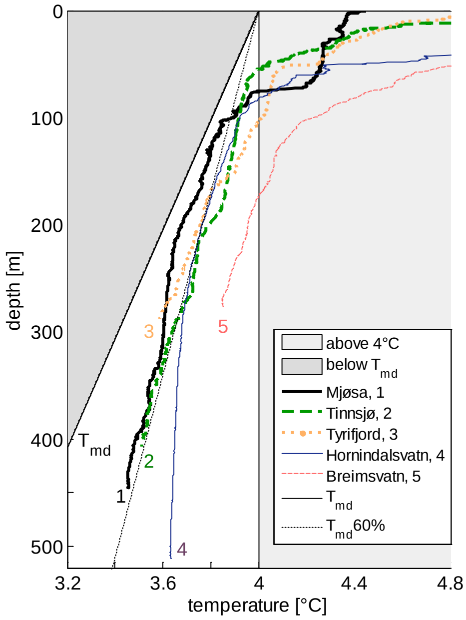

Figure 1. *temperature profiles from five Norwegian fjord lakes in spring 2006 (from Boehrer et al. 2013).*

A length ranking of the lakes corresponds perfectly with the ranking of bottom temperatures. As long lakes provide better conditions for horizontal temperature gradients, It is reasoned that the temperature profiles that establish in these very deep lakes are the result of longitudinal gradient before the onset of summer stratification.

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