FORMATION AND RAPID EXPANSION OF DOUBLE DIFFUSIVE LAYERING IN LAKE NYOS

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Summary This contribution addresses a fascinating case of double-diffusion (DD) in lakes. In Dec. 2002, 26 well-mixed layers (thicknesses: 0.2 - 2.1 m) separated by sharp interfaces were discovered in Lake Nyos – the dreaded "Killer Lake" in Cameroon – although no signs of DD have been reported since the catastrophic CO_2 eruption in 1986. The heat fluxes increased by an order of magnitude since the onset of DD convection and continuously reduce the stability, which leads to rapid expansion of the DD zone.

INTRODUCTION

Lake Nyos is a 208 m deep crater lake (surface area: 1.58 km^2) in the north-western part of Cameroon. The water column is divided into two sections by a halocline (steep chemical gradient). The upper section, the "surface-layer", is convectively mixed every year during the dry season, whereas in the lower section, the "deep-water", is not affected by this process and remains permanently stratified. Subaquatic sources introduce warm, salty and CO_2-enriched water into the deepest part of the water column [1]. Due to the high CO_2 concentration, the source water is heavier than the hypolimnetic water and thus increases the overall stability of the water column. These subaquatic sources are the reason for the permanent stratification of the water column.

In August 1986, a large CO_2 cloud erupted from the lake and asphyxiated more than 1700 people. Several processes, which will be shortly mentioned in the presentation, have been proposed as the trigger of the eruption. To prevent a new disaster, a plan for degassing the lake was developed [2]. Currently a degassing pipe with a diameter of 14.5 cm has been installed, which transports water from 203 m depth by a self-sustained fountain to the surface [2].

A characteristic of Lake Nyos is its permanent stratification which is upheld against the destratifying effect of temperature (Figure) by the high concentrations of CO_2 and salinity (whereas CO_2 is more important than salinity). Such stratification with a stabilizing and a destabilizing component, can lead to convective layers by double-diffusion (DD), if the effect of the stabilizing component is not much more than the destabilizing effect of temperature [3, 4]. The susceptibility to DD convection increases as the density ratio R_ρ decreases.

OBSERVATIONS AND RESULTS

The Figure shows a sample section of the DD zone of the CTD profile, collected in December 2002, which revealed a prominent zone of 26 well-identifiable homogeneous layers. The 0.2 to 2.1 m thick layers were distinctly separated by interfaces of strong gradients. The steps are more pronounced in the salinity than in the temperature (Figure). Surprisingly, the DD staircase was never observed before and must have developed a few months back. Before the onset of DD, the temperature at this depth was constant within the measurement resolution of 0.01 ºC, afterwards it decreased almost linearly due to the upward heat flux caused by DD. The DD convection was most probably triggered by the strong seasonal cooling in February 2002, which caused a steep temperature gradient and consequently an increased heat flux at the top of the halocline. In the case of Lake Nyos, the stabilizing factor is not only salt (TDS; Figure), but also CO_2, and subsequently we define the density ratio R_ρ [3] by

$$R_\rho = \frac{\beta_{TDS} \cdot \frac{\partial TDS}{\partial z} + \beta_{CO2} \cdot \frac{\partial [H_2CO_3]}{\partial z}}{\alpha \cdot \left(\frac{\partial T}{\partial z} - \Gamma \right)}$$

Several semi-empirical equations have been proposed to estimate the average thickness H of the steps in DD staircases. Fedorov [5] found that H depends on R_ρ and consequently on the gradients of both the temperature and the dissolved matter. In the DD zone Fedorov [5] provides layer thicknesses between 0.80 m and 1.20 m, slightly increasing with depth. The observed layer thicknesses (average 1.0 m) agree well with Federov's (average 0.9 m). The DD convection leads to an increased transport of heat, salinity and CO_2 out of the deep-water. Several parameterizations for the estimation of the temperature flux F_T have been proposed in literature. We used the semi-empirical equation [6]

$$F_{T,Kelley} = \frac{1}{(13 \pm 6)} \cdot \left(\frac{g \cdot \alpha \cdot \Delta T \cdot H^3}{D_T \cdot \nu} \right)^{0.27 \pm 0.02} \cdot \frac{\Delta T \cdot D_T}{H}$$

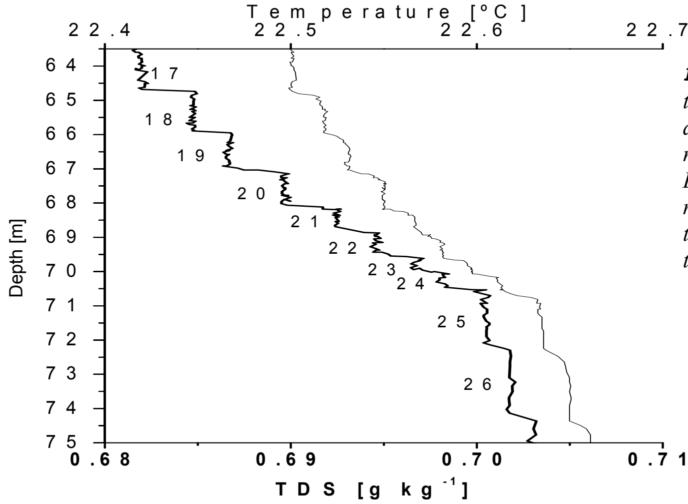

Figure: *Details of an 11-m long section from the profiles of temperature (thin line) and total dissolved solids (TDS) (thick line with layer numbers) measured on 8 December 2002 in Lake Nyos. The observed convectively well-mixed layers are numbered from the top. Note that the interfaces are much steeper for temperature than for TDS.*

and compared it to estimates from the heat budget method. For the flux law the uncertainty of the exponent of ± 0.02 given by [6] was used. The fluxes calculated by the heat budget and using the DD flux laws agree well within the range of the uncertainties and yield about 0.3 W m^{-2}. This agreement was not expected a priori, since the two methods determine the fluxes for completely different time scales. Whereas the heat budget method integrates the heat flux over 260 days, the flux law is a snapshot of the stratification at the end of this period. This agreement indicates, in combination with the nearly linear temperature trend at 62 m depth, that the DD heat flux was approximately constant in time. The heat fluxes following Turner [3] were on average 68% higher than the fluxes of Kelley [6]. The equations of Fernando [7] generally seem to under- (diffusive regime) or overestimate (low stability regime) the heat fluxes. The estimated fluxes of the dissolved components were in the range of 5 - 20 µg m^{-2} s^{-1}, of which more than 80% is CO_2. Integrating over 260 days and the area at 60 m depth, yields a total transport of about 160 t. This is only a small part of the estimated annual CO_2 input of more than 4400 t CO_2 from the deep subaquatic source [1, 8].

CONCLUSIONS

A staircase with 26 well-mixed layers at 53 to 75 m depth was formed by DD convection in Lake Nyos. The temperature profile in this zone is now rapidly transformed: At 62 m depth, the temperature decreased by 0.15 ºC within 9 months. The heat flux caused by the DD convection ranged from 0.1 W m^{-2} in the lower layers to 0.5 W m^{-2} in the upper layers of the staircase. The thicknesses of the observed steps agree well with the semi-empirical equations of Fedorov [5] and Kelley [6].

The heat fluxes based on the heat budget and on the flux laws of DD convection yield the same results within the uncertainty. The semi-empirical equation of Kelley [6] agreed better with the heat budget than Turner [3] and Fernando [7]. Without the DD convection the heat flux is dominated by molecular diffusion. Since the apparent diffusivities caused by DD are about one order of magnitude larger than the molecular diffusion coefficient, we can conclude that DD has increased the heat flux by one order of magnitude and is now the dominant cause for the vertical heat fluxes. They are similar to the heat input of the subaquatic source as estimated by Kusakabe [1] and Schmid [8]. On the contrary, the CO_2 fluxes caused by DD are negligible compared to the subaquatic input.

The current situation, with decreasing heat fluxes as a function of depth, leads to an increase in the destabilizing temperature gradient in the DD zone, which is only to a small part compensated by the CO_2 flux. If the temperature gradient is going to continue to increase, the entire zone could become unstable and a large homogenous layer could be formed within a few years. With the current CO_2 concentrations such a mixing would not be dangerous, but if the CO_2 concentration were near saturation, this process could lead to local supersaturation of CO_2 and subsequently to a new eruption. This mechanism is a possible candidate for having triggered the catastrophic eruption in 1986.

References

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