Environmental Hydraulics and Sustainable Water Management – Lee & Lam (eds)
© 2005 Taylor & Francis Group, London, ISBN 04 1536 546 5

Formation and expansion of a double-diffusive staircase in Lake Nyos, Cameroon

M. Schmid & A. Wüest
EAWAG, Limnological Research Institute, Kastanienbaum

ABSTRACT: During the dry season of the year 2002, convective cooling triggered the formation of a double-diffusive regime of the convective type below the chemocline at 52 m depth in Lake Nyos. Since then, the vertical extent of the double-diffusive staircase has continuously increased, and the front reached a depth of about 92 m in March 2004. The input of turbulent energy from wind or surface convection below the chemocline is very weak and not sufficient to disturb the development of the double-diffusive staircase. The lake represents thus a perfect natural laboratory to study the expansion and the horizontal variability of a double-diffusive staircase at a much larger scale than in laboratory experiments. Between March 2002 and March 2004, the staircase expanded vertically with a seemingly rather constant average speed of about 1.3 m per month. The formation of the double-diffusive staircase temporarily leads to a local divergence of the vertical heat flux, which also propagates downwards. The merging of layers in the upper part of the double-diffusive zone was about as frequent as the formation of new layers, keeping the number of observed layers fairly constant.

1 INTRODUCTION

1.1 *Lake Nyos*

Lake Nyos is a 208 m deep crater lake with a surface area of 1.58 km^2 in the north-western part of Cameroon. A subaquatic source introduces warm, salty and CO_2-enriched water into the deepest layers of the lake (Evans et al. 1994; Kusakabe et al. 2000; Nojiri et al. 1993; Schmid et al. 2003). The CO_2 introduced by this subaquatic source slowly accumulates in the deep waters. In August 1986, a large part of the CO_2 stored in the lake suddenly erupted, flowed down the neighboring valleys and killed more than 1700 people (Evans et al. 1994; Kling et al. 1987; Sigvaldason 1989). Since then, CO_2 had again been accumulating in the deep waters, and a new eruption was likely to occur within a few decades. To prevent a new eruption, a degassing tube has been installed in the lake which transfers water from 200 m depth to the surface (Halbwachs 2002; Halbwachs & Sabroux 2001). The water flow of 65 l s^{-1} through the tube is sustained by the buoyancy of the water-gas mixture formed in the upper part of the tube.

The CO_2 can only accumulate in the deep waters because of the very stable stratification of the lake (Figure 1). Seasonal convective mixing reaches a maximum depth of about 50 m. The deeper part of the lake, the hypolimnion, is separated from the surface waters by a chemocline, a zone with strong chemical gradients. The energy supplied to turbulent mixing by the wind action at the lake surface and by convection due to cooling of the surface waters is not sufficient to effectively penetrate the chemocline. Furthermore, internal seiches are very weak. Consequently, only very little energy is available for turbulent mixing in the hypolimnion. For this reason, the vertical profiles of temperature and conductivity change only very slowly in the hypolimnion, with the exception of the accumulation of CO_2, salts and heat from the subaquatic source in the bottom waters. Figure 2 shows that temperature remained constant within 0.1°C between 55 and 150 m depth during more than 5 years.

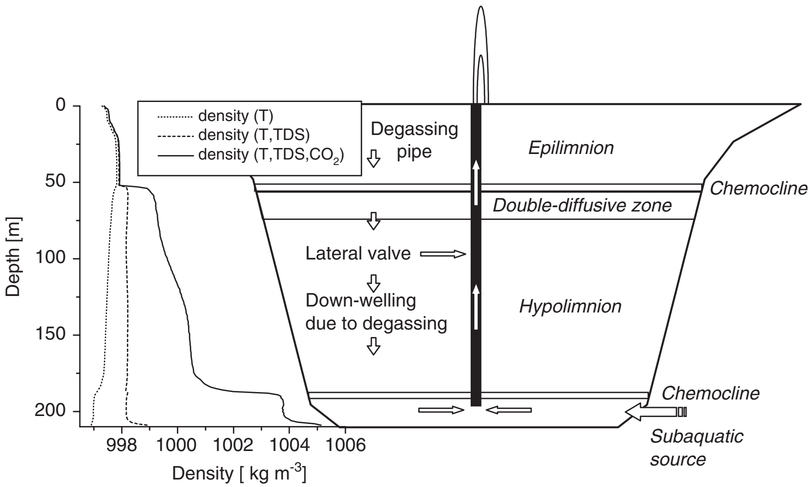

Figure 1. Overview of Lake Nyos. The graph to the left shows the contributions of temperature, total dissolved solids (TDS) and CO_2 to the density stratification of Lake Nyos in December 2002. The operation of the degassing pipe causes a down-welling of 1–3 m yr^{-1}. The double-diffusive staircase was formed below the upper chemocline.

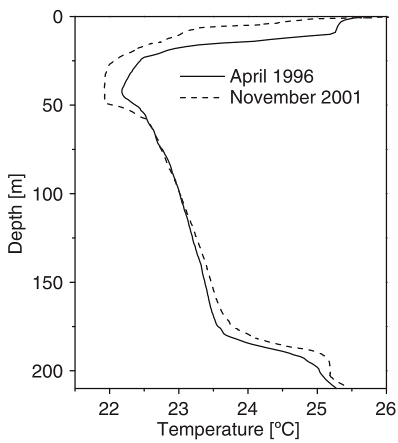

Figure 2. Vertical temperature profiles measured in Lake Nyos in April 1996 (Kusakabe et al. 2000) and November 2001.

1.2 *Double diffusive convection*

The vertical temperature profile with temperature increasing with depth would be unstable without the stabilizing effects of the dissolved substances (Figure 1). Such stratification with a stabilizing and a destabilizing component, can lead to convective layers by double-diffusion (Turner 1973) if the effect of the stabilizing component is not more than approximately 10 times as large as the destabilizing effect of temperature (Kelley et al. 2003). Staircases in vertical temperature and conductivity profiles caused by double-diffusive convection have been observed in several lakes with a diffusive regime: Lake Vanda (Hoare 1966; Huppert & Turner 1972; Spigel & Priscu 1998), Powell Lake (Osborn 1973), Lake Kivu (Lorke et al. 2004; Newman 1976), and Lake Miers (Spigel & Priscu 1998). In Lake Nyos, a double-diffusive staircase was first observed in December 2002 (Schmid et al. 2004). The double-diffusive convection caused an increase of the vertical heat fluxes by about one order of magnitude in the upper part of the double-diffusive zone. As a consequence, the temperature, which had hardly changed for years in this zone (Figure 2), decreased by 0.1–0.2°C

within less than one year. The present article describes the temporal development of this staircase between December 2002 and March 2004.

2 MEASUREMENT METHODS

2.1 *CTD profiles*

Vertical profiles of conductivity and temperature were measured with a Sea-Bird SBE19 on 8 December 2002 (6 profiles), and on 17–21 March 2004 (8 profiles). The 2002 and 2004 profiles included the measurement of pH with a Sea-Bird SBE-22B combined pH and oxygen sensor, whereas the 2001 profile did not. The pH and oxygen sensors were calibrated with pH and Winkler measurements made on water samples from several depths.

2.2 *Temperature time series*

Temperature time series were measured with Vemco minilogs and with RBR TR-1050 temperature recorders at several depths. Three Vemco minilogs were located within the double-diffusive zone: One at 62 m depth between November 2001 and December 2002, and one each on two different moorings at 58 and 60 m depths from December 2002 to March 2004.

3 RESULTS AND DISCUSSION

3.1 *Evolution of the staircase between December 2002 and March 2004*

Figure 3 shows the temperature and conductivity profiles measured in the double-diffusive zone in December 2002 and March 2004. In December 2002, the double-diffusive staircase was observed down to a depth of 74 m. From the temperature logger we know that it had reached a depth of 62 m around the end of March 2002. The staircase consequently developed with a vertical speed of about 1.4 m per month. In March 2004, the double-diffusive staircase faded out at about 95 m depth, which implies a vertical speed of about 1.3 m per month.

The number of observed mixed layers was around 25 to 30 in March 2004 as well as in December 2002, but the average thickness of the mixed layers increased by about a factor of two. In March 2004, two large mixed layers with thicknesses of about 4 and 5 m were observed, which must have been formed by the merging of several smaller layers.

In the upper part of the double-diffusive staircase, between 55 and 65 m depth, the temperature profile remained approximately constant between December 2002 and March 2004. This is also confirmed by the data from two temperature loggers at 58 and 61 m depth which showed variations of less than 0.05°C and no significant trend during this period. Below 65 m, the temperature decreased by more than 0.1°C. Only a small part of this decrease can be explained by the lowering of the whole water column due to the degassing operation, which can be estimated to ~2 m. This means that an average divergence of the heat flux of roughly 0.01 Wm^{-3} would be needed to produce the observed changes. The average heat flux must have been about 0.3 Wm^{-2} higher at 65 m than at 100 m depth, where the two temperature profiles join each other again. This divergence is very similar to that observed between 53 and 70 m depth between November 2001 and December 2002 (Schmid et al. 2004).

Conductivity in the double-diffusive zone increased during the observation period. From double diffusive-convection alone, we would expect a qualitatively similar but less important decrease in conductivity. The observed increase in conductivity indicates that there must be a salt source at this depth, which is probably the dissolution of settling particles such as iron oxides that are formed at the lake surface due to the degassing process (Schmid et al. 2004).

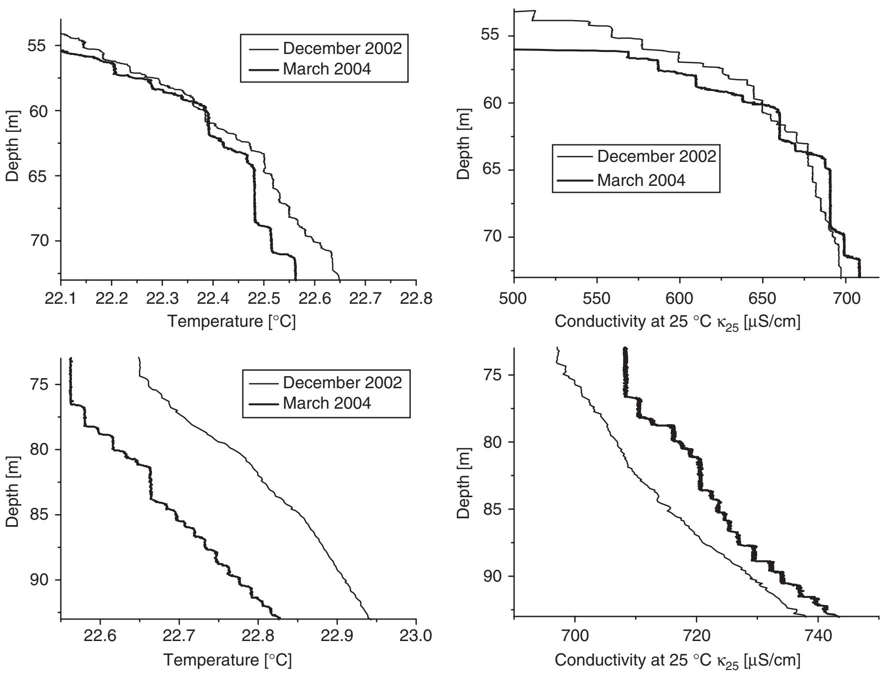

Figure 3. Vertical profiles of temperature (left panels) and conductivity at 25°C (right panels) measured in Lake Nyos in December 2002 and March 2004 between 53 and 73 m depth (upper panels) and between 73 and 93 m depth (lower panels). Note the different conductivity and temperature scales.

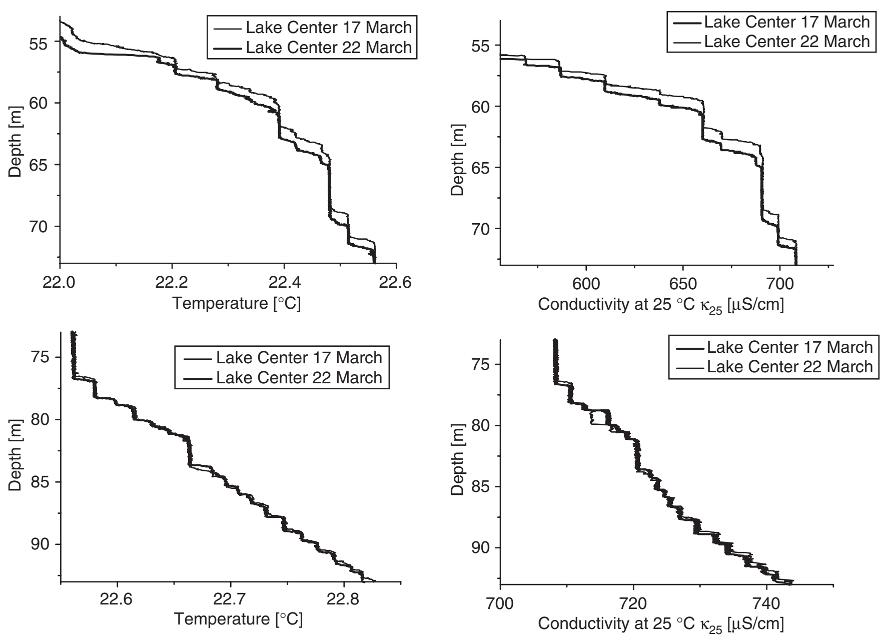

Figure 4. Vertical profiles of temperature (left panels) and conductivity at 25°C (right panels) measured in Lake Nyos on 17 and 22 March 2004 between 53 and 73 m depth (upper panels) and between 73 and 93 m depth (lower panels).

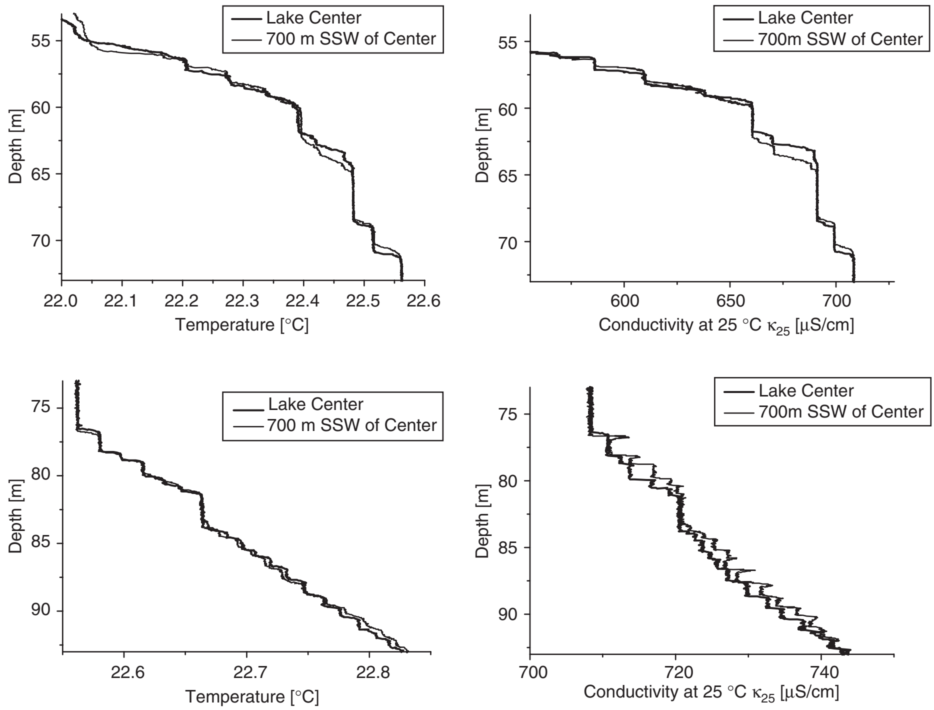

Figure 5. Vertical profiles of temperature (left panels) and conductivity at 25°C (right panels) measured in Lake Nyos at the center of the lake and near the side wall of the crater 700 m South-Southwest of the center between 53 and 73 m depth (upper panels) and between 73 and 93 m depth (lower panels).

3.2 *Local and short-time variability*

Figure 4 shows the vertical profiles of temperature and conductivity observed in the center of the lake on 17 and 22 March 2004. The profiles agree perfectly below the thick homogeneous layer at 75 m depth, above, the profile from 22 March is shifted about 80 cm upwards which must be due to internal wave motion. However, there is one exception: in one layer at 80 m depth, the conductivity increased by about 3 µS/cm. It is interesting to compare this to the observations near the steep side wall of the lake crater 700 m South-Southwest of the center (Figure 5). Profiles of conductivity and temperature at these two stations agree very well. The same mixed layers are clearly discernible in both profiles, but in several layers, the conductivity is about 2–3 µS/cm larger near the rock wall than in the center, and usually very similar to the conductivity in the next lower layer in the center. One of these layers is again the layer at 80 m depth. Furthermore, there are conductivity peaks at the top of many of these layers. Interestingly, no similar differences exist in the temperature profiles. Consequently, these signals are not due to simple mixing of water masses, but there is a source of conductivity near the rock wall which increases the conductivity of the mixed layers from the top. If we assume that this source is the dissolution of settling particles, the sedimentation must be increased near the side wall of the lake. The increased conductivity can then be transferred to the center of the lake by horizontal mixing, as seems to have happened between March 17 and 22 at the layer at 80 m depth.

4 CONCLUSIONS

The formation of a double-diffusive staircase has been triggered in Lake Nyos by convective cooling at the top of the chemocline during the dry season in February 2002. Since then, the double-diffusive

staircase has been continuously expanding downwards with an average speed of about 1.4 m per month. Within the double-diffusive zone, the heat transport is dominated by the double-diffusive convection, and about one order of magnitude larger than it was before the onset of double diffusion. The increased upwards heat flux leads to a local divergence of heat and consequently a reduction of temperature near the front of the developing staircase.

The average thickness of the observed mixed layers has increased from about 0.8 m in December 2002 to 1.5 m in March 2004. The number of observed layers remained almost constant between 25 and 30, which means that for every newly formed layer at the front of the staircase, two layers must have merged. The new layers formed between 85 and 90 m depth are around 80 cm thick. Consequently, the formation of a new layer at the front takes on average about 20 days.

The double-diffusive zone could continue to grow until it reaches the second chemocline at 185 m depth. With the current growing speed, it would take about 6 years to reach this depth. However, between 95 and 130 m depth, the stratification is less favorable for the formation of a double-diffusive staircase than above and below (Schmid et al. 2004). It will be interesting to observe in the upcoming years whether the staircase can penetrate this zone.

REFERENCES

Evans, W.C.; White, L.D.; Tuttle, M.L.; Kling, G.W.; Tanyileke, G. & Michel, R.L. 1994. Six years of change at Lake Nyos, Cameroon, yield clues to the past and cautions for the future. *Geochemical Journal* 28(3): 139–162.

Halbwachs, M. 2002. Degassing Lake Nyos project: http://perso.wanadoo.fr/mhalb/nyos/nyos.htm

Halbwachs, M. & Sabroux, J.C. 2001. Removing CO_2 from Lake Nyos in Cameroon. *Science* 292(5516): 438–438.

Hoare, R.A. 1966. Problem of heat transfer in Lake Vanda, a density stratified arctic lake. *Nature* 210: 787–789.

Huppert, H.E. & Turner, J.S. 1972. Double-diffusive convection and its implications for the temperature and salinity structure of the ocean and Lake Vanda. *Journal of Physical Oceanography* 2: 456–461.

Kelley, D.E.; Fernando, H.J.S.; Gargett, A.E.; Tanny, J. & Oezsoy, E. 2003. The diffusive regime of double-diffusive convection. *Progress in Oceanography* 56: 461–481.

Kling, G.W.; Clark, M.A.; Compton, H.R.; Devine, J.D.; Evans, W.C.; Humphrey, A.M.; Koenigsberg, E.J.; Lockwood, J.P.; Tuttle, M.L. & Wagner, G.N. 1987. The 1986 Lake Nyos gas disaster in Cameroon, West-Africa. *Science* 236(4798): 169–175.

Kusakabe, M.; Tanyileke, G.Z.; McCord, S.A. & Schladow, S.G. 2000. Recent pH and CO_2 profiles at Lakes Nyos and Monoun, Cameroon: implications for the degassing strategy and its numerical simulation. *Journal of Volcanology and Geothermal Research* 97(1–4): 241–260.

Lorke, A.; Tietze, K.; Halbwachs, M. & Wüest, A. 2004. Response of Lake Kivu stratification to lava inflow and climate warming. *Limnology and Oceanography* 49(3): 778–783.

Newman, F.C. 1976. Temperature steps in Lake Kivu: a bottom heated saline lake. *Journal of Physical Oceanography* 6: 157–163.

Nojiri, Y.; Kusakabe, M.; Tietze, K.; Hirabayashi, J.; Sato, H.; Sano, Y.; Shinohara, H.; Njine, T. & Tanyileke, G. 1993. An estimate of CO_2 flux in Lake Nyos, Cameroon. *Limnology and Oceanography* 38(4): 739–752.

Osborn, T.R. 1973. Temperature microstructure in Powell Lake. *Journal of Physical Oceanography* 3: 302–307.

Schmid, M.; Lorke, A.; Dinkel, C.; Tanyileke, G. & Wüest, A. 2004. Double-diffusive convection in Lake Nyos, Cameroon. *Deep Sea Research Part I* (in press).

Schmid, M.; Lorke, A.; Wüest, A.; Halbwachs, M. & Tanyileke, G. 2003. Development and sensitivity analysis of a model for assessing stratification and safety of Lake Nyos during artificial degassing. *Ocean Dynamics* 53: 288–301.

Sigvaldason, G.E. 1989. International Conference on Lake Nyos Disaster, Yaounde, Cameroon 16–20 March, 1987 – Conclusions and Recommendations. *Journal of Volcanology and Geothermal Research* 39(2–3): 97–107.

Spigel, R.H. & Priscu, J.C. 1998. Physical limnology of the McMurdo Dry Valleys lakes. In: J.C. Priscu (Ed.) *Ecosystem Dynamics in a Polar Desert*. Washington, D.C.: AGU.

Turner, J.S. 1973. *Buoyancy Effects in Fluids*. Cambridge: Cambridge University Press.