

Atmospheric noble gases in lake sediment pore water as proxies for environmental change

M. S. Brennwald¹

Department of Water Resources and Drinking Water, Swiss Federal Institute for Environmental Science and Technology (EAWAG), Dübendorf, Switzerland

F. Peeters²

Limnological Institute, University of Konstanz, Konstanz, Germany

D. M. Imboden

Department of Environmental Sciences, Swiss Federal Institute of Technology Zürich, Zürich, Switzerland

S. Giralt

Institute of Earth Sciences "Jaume Almera" (CSIC), Barcelona, Spain

M. Hofer, D. M. Livingstone, S. Klump, K. Strassmann, and R. Kipfer³

Department of Water Resources and Drinking Water, Swiss Federal Institute for Environmental Science and Technology (EAWAG), Dübendorf, Switzerland

Received 25 November 2003; revised 1 January 2004; accepted 13 January 2004; published 20 February 2004.

[1] Lake sediment pore water has been proposed as a noble gas archive for paleoenvironmental reconstruction, but appropriate experimental techniques have not been available until recently. Here we present noble gas concentrations measured in the sediment pore water of Lake Issyk-Kul (Kyrgyzstan) which demonstrate for the first time the value of the sediment pore water archive for paleoclimate reconstruction. The noble gas profiles in the sediment indicate that the salinity of the lake water during the mid-Holocene was more than twice its present value of 6.0 g/kg, implying a 200-m lower lake level. *INDEX TERMS*: 1845 Hydrology: Limnology; 1065 Geochemistry: Trace elements (3670); 9320 Information Related to Geographic Region: Asia; 1099 Geochemistry: General or miscellaneous. **Citation**: Brennwald, M. S., F. Peeters, D. M. Imboden, S. Giralt, M. Hofer, D. M. Livingstone, S. Klump, K. Strassmann, and R. Kipfer (2004), Atmospheric noble gases in lake sediment pore water as proxies for environmental change, *Geophys. Res. Lett.*, 31, L04202, doi:10.1029/2003GL019153.

1. Introduction

[2] The concentrations of dissolved atmospheric noble gases in lakes correspond closely to the atmospheric equilibrium concentrations given by the in situ temperature T , the salinity S and the mean atmospheric pressure p [Aeschbach-Hertig *et al.*, 1999; Peeters *et al.*, 2000]. During sedimenta-

tion, part of the water is incorporated into the sediment pore space. The noble gas concentrations in the pore water are therefore expected to carry information about the past physical conditions pertaining in the overlying water [Barnes, 1979; Brennwald *et al.*, 2003], as do the noble gas concentrations in paleo-groundwaters [Mazor, 1972; Stute *et al.*, 1995; Beyerle *et al.*, 1998, 2003].

2. Study Site

[3] Lake Issyk-Kul, one of the world's largest high-altitude lakes, is 668 m deep and is situated in a semi-arid environment. Today it has no outflow and is therefore slightly saline (6.0 g/kg). Such closed lakes are known to show large changes in lake level and salinity in response to changes in local climate [Fritz, 1996]. Submerged river valleys, terraces and delta lobes in Lake Issyk-Kul indicate previous lake levels, probably during the middle Holocene or earlier, that were several hundred meters below the present level [De Batist *et al.*, 2002]. Previous paleolimnological studies suggest that lake level and salinity have been highly variable during the Holocene [Ricketts *et al.*, 2001]. Further, the existence of submerged early settlements and evidence from historical documents suggest that the lake level has varied considerably even during the last millennium [Romanovsky, 2002].

[4] A multi-proxy study of the uppermost 2 m of the sediment at our sampling site [Giralt *et al.*, 2002] indicates a period of substantially lower lake level than at present. The sediment is divided into two main lithological units: homogeneous clay (0–15 cm) and laminated silty clay (15–200 cm). The mineralogical composition of the sediment (Figure 1) indicates changes in the depositional environment. Magnesian calcite predominates between 83 and 97 cm, but is absent above and below this zone, where calcite (and monohydrocalcite) predominate. The precipitation of magnesian calcite is attributed to high Mg/Ca ratios

¹Also at Department of Environmental Sciences, Swiss Federal Institute of Technology Zürich, Zürich, Switzerland.

²Also at Department of Water Resources and Drinking Water, Swiss Federal Institute for Environmental Science and Technology (EAWAG), Dübendorf, Switzerland.

³Also at Department of Isotope Geology, Swiss Federal Institute of Technology Zürich, Zürich, Switzerland.

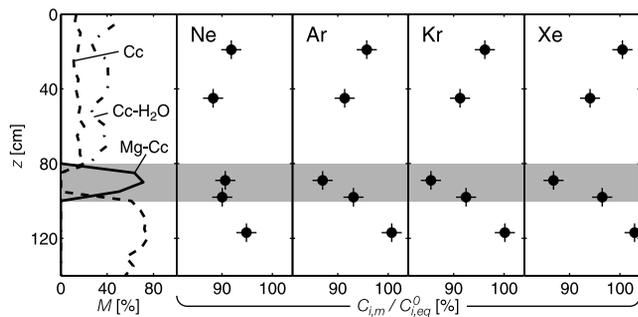


Figure 1. Mineralogical sediment composition (M) and noble gas concentrations in the pore water ($C_{i,m}$) plotted against sediment depth z . M is the mass fraction of the respective carbonate species per unit total mass of dry sediment (Cc: calcite, Mg-Cc: magnesian calcite, Cc-H₂O: monohydrocalcite). The measured noble gas concentrations $C_{i,m}$ ($i = \text{Ne, Ar, Kr, Xe}$) are normalized to the equilibrium concentrations in the overlying water ($C_{i,eq}^0$) corresponding to the present annual mean temperature (4.5°C), salinity (6.0 g/kg) and atmospheric pressure (823.6 hPa). Equilibrium concentrations were calculated using the empirical solubility data recommended by Kipfer *et al.* [2002]. The error bars indicate the total analytical uncertainties.

in the water due to the evaporative concentration of Mg and the loss of Ca by calcite precipitation [Eugster and Hardie, 1978]. The magnesian calcite peak therefore suggests higher salinity and a lower lake level, which is in line with further proxies in the sediment: between 86 and 136 cm (i) the sediment is coarser (with a mean grain size of 16 μm in contrast to 8 μm above and below), (ii) fecal pellets from shallow-water organisms are present, and (iii) the pollen record indicates a higher fraction of wetland vegetation which might have been present in swamp environments that formed on shallow littoral areas exposed when the lake level was lower. The uppermost 10 cm of the sediment was dated using the ^{210}Pb and ^{137}Cs methods [Giralt *et al.*, 2004]. Extrapolating this chronology to the magnesian calcite peak suggests that the lowest lake level occurred about 2 kyr B.P. However, ^{14}C data from a different sediment core suggest that the sediment zone rich in magnesian calcite was deposited during the mid-Holocene [Ricketts *et al.*, 2001].

3. Noble Gas Sampling and Analysis

[5] A 122-cm long sediment core was taken at 77°19.924'E / 42°34.267'N (in 323 m water depth) using a gravity corer. Bulk sediment was transferred from this core into the sample containers (Cu tubes) without exposure to the atmosphere or other gas reservoirs. The noble gases were then extracted from the pore water by degassing the sediment in an evacuated extraction vessel [Brennwald *et al.*, 2003]. The noble gas abundance was then analyzed with an overall 1σ uncertainty of 2% [Brennwald *et al.*, 2003] following standard mass spectrometric procedures [Beyerle *et al.*, 2000]. Sampling depths were 19 cm, 45 cm, 89 cm, 98 cm and 117 cm. The uncertainty in sampling depth was estimated as about 5 cm by inspection of the sediment core after sampling. Helium produced in the sediment minerals

by radioactive decay is partially released during analysis [Brennwald *et al.*, 2003]. Hence, the He data are affected by the radiogenic He component and were not considered in this study.

4. Results and Discussion

[6] All Ar, Kr, and Xe concentrations in the open water agree with the atmospheric equilibrium concentrations computed from the in situ water temperature, salinity and mean atmospheric pressure within analytical uncertainties (Water samples for noble gas analyses, with an analytical 1σ uncertainty of 1%, were collected from the central part of the lake (77°8.305'E / 42°24.429'N) at depth intervals of 50 m [Hofer *et al.*, 2002]). A small but negligible Ne excess (<4%) was observed which can be attributed to the dissolution of air bubbles entrapped by breaking waves [Hofer *et al.*, 2002; Wu, 2000].

[7] In the sediment, the measured Ar, Kr and Xe concentrations show distinct minima at about 90 cm below the sediment surface (Figure 1). Ne shows a similar but less pronounced pattern. Extrapolating the concentrations of Ar, Kr and Xe up to the sediment surface yields the same concentrations as those observed in the overlying water. A qualitatively similar noble gas concentration profile was observed in a second sediment core taken at a deeper sampling site. The lithology, mineralogical composition and sedimentation rate of this core are, however, unknown and the noble gas data will therefore not be considered further.

[8] The in situ noble gas abundance in pore water may be altered by degassing into gas bubbles forming in the sediment [Brennwald *et al.*, 2003] due to supersaturation of dissolved gases such as CH₄. In Lake Issyk-Kul, however, methanogenesis is limited because the entire water column is permanently oxygenated [Hofer *et al.*, 2002; Karmanchuk, 2002; Vollmer *et al.*, 2002]. Also, during sediment sampling we observed no gas bubbles forming in the sediment despite the large decrease in hydrostatic pressure that occurred during recovery of the sediment core. Yet, the Ne concentration in the uppermost sediment sample is about 8% lower than the present equilibrium concentration in the overlying water, which may point to slight Ne degassing. Due to the higher solubility of Ar, Kr and Xe, these gases are less sensitive to degassing than Ne. The respective losses of Ar, Kr, and Xe calculated from the Ne undersaturation by assuming gas equilibration with gas bubbles initially free of noble gases [Brennwald *et al.*, 2003] are within analytical uncertainties (2%), and were therefore neglected.

[9] Diffusion often controls the vertical transport of solutes in pore water [Boudreau, 1997]. If this is the case here, the depths z_i to which the noble gas signals penetrate the sediment column can be estimated from the Einstein-Smoluchowski relation $z_i = \sqrt{2D_i t}$ (where D_i is the effective diffusivity of the noble gas i and t is the travel time of the signals). The ratio of the molecular diffusivity of Ar to that of Xe is 2.1. Assuming the diffusive pathways in the pore space to be the same for Ar and Xe, the ratio of the effective diffusivities of Ar and Xe in the pore space, D_{Ar}/D_{Xe} , is also 2.1, yielding $z_{Ar}/z_{Xe} \approx 1.5$. Analogously, $z_{Ar}/z_{Kr} \approx 1.3$. However, this disagrees with the measured noble gas

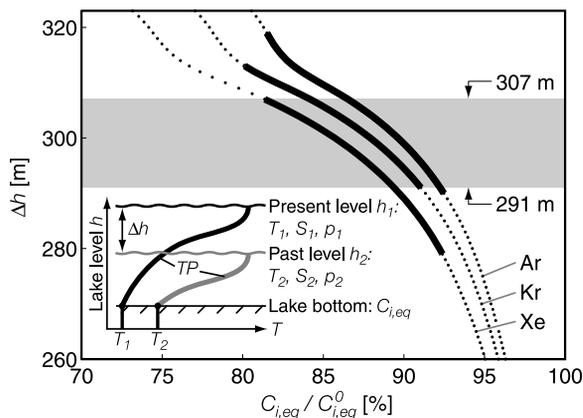


Figure 2. Estimate of the minimum lake level indicated by the measured noble gas profiles. The modeled noble gas concentrations $C_{i,eq}$ ($i = Ar, Kr, Xe$) are expressed as a function of the change in lake level Δh , and are normalized to the equilibrium concentrations in the overlying water ($C_{i,eq}^0$) computed from the present annual mean water temperature at the sediment surface (T_1), salinity (S_1) and atmospheric pressure at the water surface (p_1). T_2 , S_2 and p_2 are the respective modeled values during a period of lower lake level in the past (see text). The annual mean temperature profile TP (1981–1986) was used to model $C_{i,eq}$ because the noble gas concentrations in the pore water reflect the annual mean temperature [Brennwald et al., 2003]. For simplicity, the shape of this profile relative to the water surface was assumed to be unaffected by lake level changes. The solid parts of the curves reflect the analytical 2σ uncertainty range of the measured minimum concentrations in Figure 1. In the range $291 \text{ m} < \Delta h < 307 \text{ m}$ all modeled concentrations simultaneously match the measured minimum concentrations within the limits of analytical uncertainty (grey bar). The figure also illustrates that if the noble gas signals in the sediment had been attenuated by diffusion, the respective unattenuated signals (i.e., lower concentrations) would correspond to a greater change in lake level ($\Delta h > 307 \text{ m}$).

data, because, within the vertical resolution of the measurements, the respective peaks are all found at the same depth (Figure 1). Diffusion must therefore be strongly limited and is insufficient to decouple the Ar, Kr, and Xe signals in the pore water from the sediment matrix. Hence, advection (sediment accumulation) outweighs diffusion, and the respective Peclet numbers [Schwarzenbach et al., 2003] $Pe_i = \omega L/D_i$ must be large (where ω is the sedimentation rate and L is the depth of the concentration minima in the sediment). Now $\omega \leq 0.5 \text{ mm/yr}$ and $L \approx 0.9 \text{ m}$, yielding a rough estimate for the effective noble gas diffusivities in the sediment: $D_i \ll \omega L \leq 4.5 \cdot 10^{-4} \text{ m}^2/\text{yr}$. The effective noble gas diffusivities D_i are therefore smaller than the respective molecular diffusivities in water ($>10^{-2} \text{ m}^2/\text{yr}$) by two orders of magnitude or more, which is comparable to previously reported diffusivity restrictions in clay [Horseman et al., 1996]. This substantial restriction of the vertical diffusion is attributed to the low permeability and the anisotropy of the clayish and laminated sediment, and to the Renkin effect [Renkin, 1954], which may reduce diffusion if the diameter

of the connections between the pores is on the order of $1 \mu\text{m}$ or less.

[10] In consequence, the form of the observed noble gas profiles must be due to changes in the paleoenvironmental conditions governing the noble gas concentrations in the lake. The noble gas data were interpreted in terms of lake level changes by linking the lake level to the atmospheric pressure at the lake surface, the water salinity, and the water temperature at the sediment surface. These three variables were simultaneously computed as functions of the lake level h (height above sea-level) using the following, simplified approach. (i) The mean atmospheric pressure p at the water surface is given by the barometric formula $p(h) = 1013.25 \text{ hPa} \times \exp(-h/h_0)$, where the value of h_0 relevant for Lake Issyk-Kul (7.76 km) was determined from the present mean atmospheric pressure at the present lake surface elevation. (ii) The salinity $S(h)$ is inversely proportional to the volume of the water body $V(h)$ (as given by Tsigelnaya [1995]), i.e., the total mass of dissolved salt in the lake is assumed constant. This assumption is justified because the residence time of the major solutes in the lake is about 30 kyr or more [Tsigelnaya, 1995; Lyons et al., 2000]. (iii) The water temperature at the sediment surface is also assumed to depend on water level because the distance from sediment to lake surface decreases with decreasing water level. Heat transport from the lake surface therefore leads to higher water temperatures in shallower waters. For simplicity, the relevant temperature at the sediment surface $T(h)$ was assumed to follow the present annual mean temperature profile as illustrated in Figure 2.

[11] Comparing the measured minimum noble gas concentrations in the pore water with the equilibrium concentrations $C_{i,eq}(h)$ computed from the above functions $p(h)$, $S(h)$, and $T(h)$ yields a rough estimate for the lake level in the past. Ar, Kr and Xe unambiguously indicate a past lake level 290–310 m lower than the present level (Figure 2). The measured Ne concentrations were not considered for this estimate because the possibility of Ne degassing cannot be excluded, and because Ne is less sensitive to temperature and salinity changes than are the other noble gases. Note that if the Ar, Kr, and Xe signal amplitudes were substantially attenuated due to diffusion, the respective unattenuated signals would indicate an even lower lake level (Figure 2). However, as the sediment considered here was continuously submerged, the lake level cannot at any time have been lower than 323 m below its present level. The measured Ar, Kr and Xe signals cannot therefore have been overly attenuated. In the shallow shelf regions the thermocline is up to 35 m deeper than in the central part of the lake [Romanovsky and Shabunin, 2002]. To assess the effect of this, Δh was re-estimated using the above temperature profile shifted downwards by 35 m. This showed that Δh may have been overestimated by 34 m. The past lake surface inferred from our noble gas data was therefore at least 250 m below its present level.

5. Conclusions

[12] This study demonstrates that noble gas records from sediment pore water can and do provide information on past environmental conditions in lakes. The minimum lake level of Lake Issyk-Kul suggested by the noble gas data is similar to that indicated by the bathymetry of the lake basin. The

noble gas analysis provides results consistent with those from more traditional analyses of the sediment matrix, indicating that noble gas analyses can complement traditional sedimentological methods in assessing past long-term changes in lacustrine environments. The success of this study also suggests that dissolved noble gases in the pore water of marine sediments should be reconsidered as promising proxies for paleoclimate reconstruction.

[13] **Acknowledgments.** Thanks are due to the crew of the Moltur for their excellent support and for the pleasant atmosphere that prevailed during the expedition. This research was made possible by funding from the Swiss Science Foundation (SNF 2000-068191) and from the European Union within the framework of the INCO/COPERNICUS Project APELIK ("Assessment and Prognosis of Environmental Changes in Lake Issyk-Kul [Kyrgyzstan]"; contract ICA2-CT-2000-10003).

References

- Aeschbach-Hertig, W., F. Peeters, U. Beyerle, and R. Kipfer (1999), Interpretation of dissolved atmospheric noble gases in natural waters, *Water Resour. Res.*, **35**, 2779–2792.
- Barnes, R. O. (1979), Operation of the IPOD in situ pore water sampler, in *Initial Reports of the Deep Sea Drilling Project*, vol. 47, part 2, edited by J. Sibuet and W. Ryan, pp. 19–22, U.S. Govt. Print. Off., Washington, D. C.
- Beyerle, U., R. Purtschert, W. Aeschbach-Hertig, D. M. Imboden, H. H. Loosli, R. Wieler, and R. Kipfer (1998), Climate and groundwater recharge during the last glaciation in an ice-covered region, *Science*, **282**, 731–734.
- Beyerle, U., W. Aeschbach-Hertig, D. M. Imboden, H. Baur, T. Graf, and R. Kipfer (2000), A mass spectrometric system for the analysis of noble gases and tritium from water samples, *Environ. Sci. Technol.*, **34**, 2042–2050.
- Beyerle, U., J. Rüedi, M. Leuenberger, W. Aeschbach-Hertig, F. Peeters, R. Kipfer, and A. Dodo (2003), Evidence for periods of wetter and cooler climate in the Sahel between 6 and 40 kyr BP derived from groundwater, *Geophys. Res. Lett.*, **30**(4), 1173, doi:10.1029/2002GL016310.
- Boudreau, B. P. (1997), *Diagenetic Models and Their Implementation: Modelling Transport and Reactions in Aquatic Sediments*, Springer-Verlag, New York.
- Brennwald, M. S., M. Hofer, F. Peeters, W. Aeschbach-Hertig, K. Strassmann, R. Kipfer, and D. Imboden (2003), Analysis of dissolved noble gases in the pore water of lacustrine sediments, *Limnol. Oceanogr. Methods*, **1**, 51–62. (Available at <http://aslo.org/lomethods/free/2003/0051.pdf>.)
- De Batist, M., et al. (2002), Bathymetry and sedimentary environment of Lake Issyk-Kul, Kyrgyz Republic (Central Asia): A large, high-altitude, tectonic lake, in *Lake Issyk-Kul: Its Natural Environment, NATO Sci. Ser. IV: Earth and Environ. Sci.*, vol. 13, edited by J. Klerkx and B. Imanackunov, pp. 101–123, Kluwer Acad., Norwell, Mass.
- Eugster, H., and L. Hardie (1978), Saline Lakes, in *Lakes: Chemistry, Geology, Physics*, edited by A. Lerman, pp. 237–293, Springer-Verlag, New York.
- Fritz, S. C. (1996), Paleolimnological records of climatic change in North America, *Limnol. Oceanogr.*, **41**, 882–889.
- Giralt, S., J. Klerkx, S. Riera, R. Julia, V. Lignier, C. Beck, M. De Batist, and I. Kalugin (2002), Recent paleoenvironmental evolution of Lake Issyk-Kul, in *Lake Issyk-Kul: Its Natural Environment, NATO Sci. Ser. IV: Earth and Environ. Sci.*, vol. 13, edited by J. Klerkx and B. Imanackunov, pp. 125–145, Kluwer Acad., Norwell, Mass.
- Giralt, S., et al. (2004), 1,000-years of environmental history of Lake Issyk-Kul, in *Dying and Dead Seas: Climatic Versus Anthropogenic Causes, NATO ARW/ASI Ser.*, edited by J. Nihoul and P. Zavialov, Kluwer, Acad., Norwell, Mass., in press.
- Hofer, M., F. Peeters, W. Aeschbach-Hertig, M. Brennwald, J. Holoher, D. M. Livingstone, V. Romanovski, and R. Kipfer (2002), Rapid deep-water renewal in Lake Issyk-Kul (Kyrgyzstan) indicated by transient tracers, *Limnol. Oceanogr.*, **47**, 1210–1216.
- Horseman, S., J. Higgs, J. Alexander, and J. Harrington (1996), Water, gas and solute movement through argillaceous media, *Tech. Rep. CC-96/1*, Nucl. Energy Agency, Org. for Econ. Coop. Dev., Paris.
- Karmanchuk, A. S. (2002), Water chemistry and ecology of Lake Issyk-Kul, in *Lake Issyk-Kul: Its Natural Environment, NATO Sci. Ser. IV: Earth and Environ. Sci.*, vol. 13, edited by J. Klerkx and B. Imanackunov, pp. 13–26, Kluwer Acad., Norwell, Mass.
- Kipfer, R., W. Aeschbach-Hertig, F. Peeters, and M. Stute (2002), Noble gases in lakes and ground waters, in *Noble Gases in Geochemistry and Cosmochemistry, Rev. Mineral. Geochem.*, vol. 47, edited by D. Porcelli, C. Ballentine, and R. Wieler, pp. 615–700, Mineral. Soc. of Am., Washington, D. C.
- Lyons, W. B., K. A. Welch, J.-C. Bonzongo, and E. Y. Graham (2000), A preliminary assessment of the geochemical dynamics of Issyk-Kul Lake, Kirghizstan, *Limnol. Oceanogr.*, **46**, 713–718.
- Mazor, E. (1972), Paleotemperatures and other hydrological parameters deduced from gases dissolved in groundwaters, Jordan Rift Valley, Israel, *Geochim. Cosmochim. Acta*, **36**, 1321–1336.
- Peeters, F., R. Kipfer, D. Achermann, M. Hofer, W. Aeschbach-Hertig, U. Beyerle, D. M. Imboden, K. Rozanski, and K. Fröhlich (2000), Analysis of deep-water exchange in the Caspian Sea based on environmental tracers, *Deep Sea Res., Part 1*, **47**, 621–654.
- Renkin, E. M. (1954), Filtration, diffusion, and molecular sieving through porous cellulose membranes, *J. Gen. Physiol.*, **38**, 225–243.
- Ricketts, R. D., T. C. Johnson, E. T. Brown, K. A. Rasmussen, and V. A. Romanovsky (2001), The Holocene paleolimnology of Lake Issyk-Kul, Kyrgyzstan: Trace element and stable isotope composition of ostracodes, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **176**, 207–227.
- Romanovsky, V. V. (2002), Water level variations and water balance of Lake Issyk-Kul, in *Lake Issyk-Kul: Its Natural Environment, NATO Sci. Ser. IV: Earth and Environ. Sci.*, vol. 13, edited by J. Klerkx and B. Imanackunov, pp. 45–57, Kluwer Acad., Norwell, Mass.
- Romanovsky, V. V., and G. D. Shabunin (2002), Currents and vertical water exchange in Lake Issyk-Kul, in *Lake Issyk-Kul: Its Natural Environment, NATO Sci. Ser. IV: Earth and Environ. Sci.*, vol. 13, edited by J. Klerkx and B. Imanackunov, pp. 77–87, Kluwer Acad., Norwell, Mass.
- Schwarzenbach, R. S., P. M. Gschwend, and D. M. Imboden (2003), *Environmental Organic Chemistry*, 2nd ed., John Wiley, Hoboken, N. J.
- Stute, M., M. Forster, H. Frischkorn, A. Serejo, J. F. Clark, P. Schlosser, W. S. Broecker, and G. Bonani (1995), Cooling of tropical Brazil (5°C) during the Last Glacial Maximum, *Science*, **269**, 379–383.
- Tsigelnaya, I. D. (1995), Issyk-Kul' Lake, in *Enclosed Seas and Large Lakes of Eastern Europe and Middle Asia*, edited by A. F. Mandych, pp. 199–229, SPB Acad., Amsterdam.
- Vollmer, M. K., R. F. Weiss, P. Schlosser, and R. T. Williams (2002), Deep-water renewal in Lake Issyk-Kul, *Geophys. Res. Lett.*, **29**(8), 1283, doi:10.1029/2002GL014763.
- Wu, J. (2000), Bubbles produced by breaking waves in fresh and salt waters, *J. Phys. Oceanogr.*, **30**, 809–813.
- M. S. Brennwald, M. Hofer, R. Kipfer, S. Klump, D. M. Livingstone, and K. Strassmann, Department of Water Resources and Drinking Water, EAWAG, CH-8600 Dübendorf, Switzerland. (brennmat@eawag.ch; hofer@eawag.ch; kipfer@eawag.ch; klumpste@eawag.ch; living@eawag.ch; strassku@eawag.ch)
- S. Giralt, Institute of Earth Sciences "Jaume Almera" (CSIC), Lluís Solé i Sabarís, E-08028 Barcelona, Spain. (sgiralt@ija.csic.es)
- D. M. Imboden, Department of Environmental Sciences, ETH, CH-8092 Zürich, Switzerland. (imboden@env.unw.ethz.ch)
- F. Peeters, Limnological Institute, University of Konstanz, D-78457 Konstanz, Germany. (frank.peeters@uni-konstanz.de)