A preliminary investigation of some chemical and physical profiles of Lake Tanganyika

Student: Felicity Smith
Mentor: Dr. Pierre-Denis Plisnier

Introduction

Lake Tanganyika is located between 3º20' - 8º45' South and 29º05' and 31º15' East, at an elevation of 773m. The lake's mean depth is 570m, with a maximum depth of 1470m in the south basin. The maximum depth of the north basin is 1310m, and the maximum depth of the Kalemie shoal, which lies between the north and south basins, is 885m (Figure 1).

Lake Tanganyika is a permanently stratified East African rift lake (Coulter, 1991). The characteristics of its deep waters have seldom been studied; most studies have focused on the epilimnion. The goal of this study was to characterize the limnological profile of the entire water column in the lake's north and south basins. Changes in chemical composition in the water column are linked to physical and biological changes. Lake Tanganyika's internal waves and currents and associated turbulence move masses of water, and biological communities alter the composition of the water they inhabit. Examining the chemical profiles of the water column helps us understand the lake's physical and biological processes.

Methods

I sampled in the north basin at S5º03' E29º32' on 18 July 2001, and in the Kalemie sub-basin at S6º34' E29º49'on 21 and 22 July 2001 (CTD and water samples 150m to 700m on 21 July, water samples 0m to 150m on 22 July) (Figure 1). GPS points were recorded at the start and finish of each sampling period. Three secchi readings were taken at the outset of sampling each day. I did a cast with a Seabird Seacat SBE 19 CTD for the entire water column at the outset of sampling. The CTD recorded depth, temperature, conductivity and dissolved oxygen (D.O.) every 0.5 seconds. Data from the CTD's descent were used in analysis. I used three sampling bottles attached to a winch-operated steel cable, so that water samples were taken at three depths at a time. Alkalinity and pH were analyzed immediately, with a Melrohm AG Titrino, which titrated 2 mL samples with 10mM HCl to a pH 4.3 endpoint. Water samples were placed in a freezer for transportation back to land, but the freezer was unreliable and the samples were often refrigerated, but not frozen, until the cruise ended on 25 July 2001. I performed lab analyses with a HACH DR/2010 spectrophotometer. Unfiltered samples were analyzed for total phosphorus and silica (SiO_2), and samples were filtered through Whatman GF/C glass fiber filters before they were analyzed for soluble reactive phosphorus, nitrate (NO_3-N), nitrite (NO_2-N) and ammonium (NH_4-N). SiO_2 was measured from 0m to 100m using the heteropoly blue method for low-range silica, and from 100m to 1100m using the silicomolybdate method for high range silica. Soluble reactive phosphorus was measured using the ascorbic acid method, nitrate with the cadmium reduction method, nitrite with the diazotization chromotropic acid method, and ammonium with the salicylate method for low range ammonium. Concentration of CO_2, HCO_3^-, and CO_3^{2-} were calculated from the pH and alkalinity data.

Results

Average secchi depths for the three sampling days were 12.9m (18 July), 9.0m (21 July), and 7.7m (22 July). The temperatures of the deep waters of the two basins are very similar (minimum 23.31ºC at 857m in the north basin, 23.42ºC at 542m in the south), but the surface water in the north basin is warmer (maximum 26.12ºC at 0m in the north basin, 25.32ºC at 0m in the south) (Figure 2). The thermocline is at 75m in the north, and at 84m in the south. There is a slight warming below 860m in the north basin, and below 500m in the south basin. At 700m, the north basin is slightly cooler than the south basin (23.39ºC in the north, 23.46 in the south). Dissolved oxygen follows the same general trend as temperature, with the oxycline occurring at 75m in the north basin, and at 82m in the south basin (Figure 3). The two basins have roughly parallel D.O. curves. The D.O. values only reach 4.84mg/L in the epilimnion, because the D.O. meter was not calibrated. Below the oxycline, from 90m to 170m, the dissolved oxygen values fluctuate.

Fig. 1. Sampling Locations

Fig. 2. Temperature v. Depth

Fig. 3. Dissolved Oxygen v. Depth

Fig. 4. Conductivity v. Depth
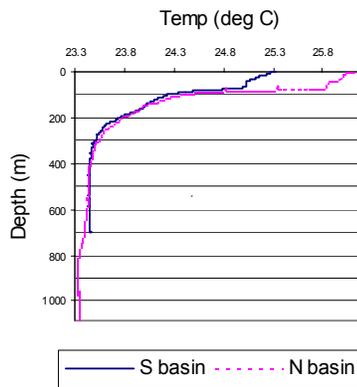
Fig 5. Alkalinity v. Depth

Fig. 6. pH v. Depth

Fig. 7. [NO3] and [NH4] v. Depth
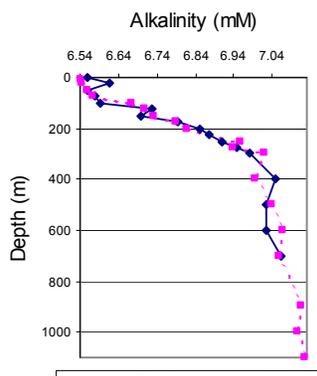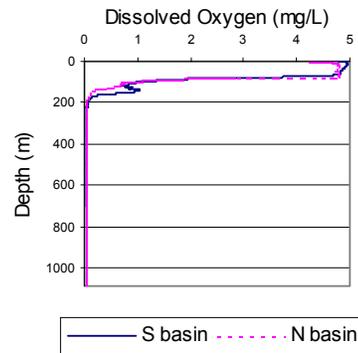
Fig. 8. Silica Concentration v. Depth
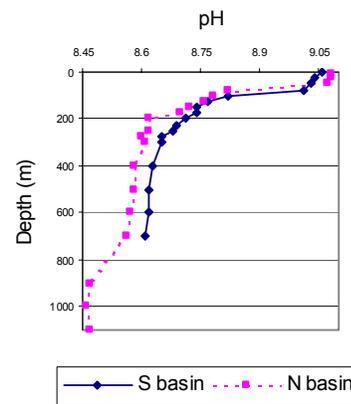
Fig. 9. Total Dissolved Inorganic Carbon v. Depth
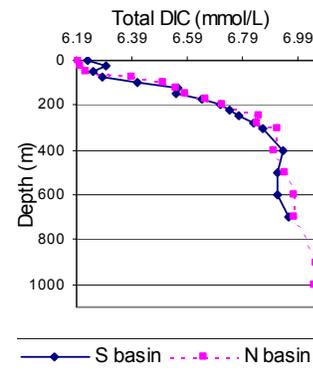
The water is anoxic below 170m. Conductivity in the north basin ranges from 666µS/cm (at 117m) to 692µS/cm (at 1079m), and in the south basin it is lower, ranging from 662µS/cm (at 36m) to 685µS/cm (at 694m). Conductivity is higher in the north basin than in the south basin until 200m, and from this point until 700m (where sampling stopped in the south basin) it is higher in the south basin than in the north basin. In both basins conductivity increases from about 150m to the lowest sampling point. Both sites have a peak around 80m.

Alkalinity ranges from 6.54meq/L $CaCO_3$ (at 0m) to 7.13meq/L $CaCO_3$ (at 1100m) in the north basin, and from 6.56 meq/L $CaCO_3$ (at 0m) to 7.07meq/L $CaCO_3$ (at 700m) in the south basin (Figure 5). The values for the two basins are parallel, increasing from top to bottom, showing the most dramatic increase between 100m and 300m. The pH values range from 8.46 to 9.08 in the north basin, and from 8.61 to 9.06 in the south basin (Figure 6). The values from the two basins are parallel. They decrease from top to bottom, with the largest change between 50m and 150m.

Ammonium (NH_4-N) is essentially not present until 200m, and its highest value in both basins occurs in the deepest water (0.86mg/L at 1100m in the north basin, 0.50mg/L at 700m in the south basin) (Figure 7). Nitrate peaks at 100m in both basins (0.08mg/L north, 0.11mg/L south). In both basins, the nitrite curve has a relative minimum at the same depth as the nitrate peak (100m) (0.017mg/L north, 0.011mg/L south). At the sampling point just below this (150m), both basins show a relative maximum of nitrite (0.018mg/L north, 0.017mg/L south). These nitrite fluctuations are much more pronounced in the south basin. Throughout the profile, nitrite concentrations remain very low in relation to nitrate and ammonium concentrations. For this reason, nitrite is not included in Figure 7. The data for total and soluble reactive phosphorus were discarded because the samples were not adequately preserved. Silica is lowest in the upper waters of both basins (minimum 0.467mg/L north, 0.973mg/L south) (Figure 8). In the south basin, silica increases with depth but changes little (13.6mg/L to 13.4mg/L) from 400m to 700m, and in the north basin it increases down to 600m, and decreases from 600m to 1100m.

Total dissolved inorganic carbon (DIC), carbon dioxide and bicarbonate increase with depth, and carbonate decreases with depth (Figures 9, 10, 11, 12). The greatest change in all of these parameters occurs between 50m and 100m in both basins. Total DIC, CO_2 and HCO_3^- are usually lower in the south basin, whereas CO_3^{2-} is usually lower in the north basin. This pattern is reversed for all parameters in the upper 50m of the water column.

Discussion

When the temperature data I obtained are compared to historical data (Adams and Charles, 2000; Edmond *et al.*, 1993; Craig *et al.* 1974), several patterns emerge (Figure 13). In all years when samples were taken in both the north and south basins, at the surface the north basin is warmer, but in the deep hypolimnion it is cooler. The wind that blows over Lake Tanganyika during the dry season (May – September) comes predominantly from the south. This wind tilts the thermocline down toward the north and causes upwelling at the lake's southern end (Coulter, 1991) (Figure 14). The water in southern basin is more mixed than the water in the north basin, which accounts for the straighter, more weakly stratified temperature profile of the south basin. The south basin is also farther from the equator, and becomes colder during the night and therefore does not stratify as strongly. The thermocline is 9m deeper in the south than in the north. This difference can also be explained by the dry season winds, which are stronger in the south basin, driving the mixolimnion deeper in the south than it is in the north.

Five out of the seven temperature profiles exhibit the second pattern, which is a slight warming in the deepest water. The warming begins an average of 220m (from 146m to 269m) from the bottom, and happens all the way to the lowest water sampled. It occurs at a given distance from the lake bottom, not at a given depth. This warming may be due to geothermal heat flux (B. Wehrli, pers. comm.). Coulter (1968) found the same pattern in Lake Malawi and noted that "terrestrial heat flow at the lake bottom may be significant." He also mentioned that compression could cause a temperature rise of about 0.2°C under 1000m of water.

Fig. 10. [HCO3] v. Depth

[HCO3] (mmol/L)

S basin   N basin

Fig. 11. [CO2] v. Depth

[CO2] (mmol/L)

S basin   N basin

Fig. 12. [CO3] v. Depth

[CO3] (mmol/L)

S basin   N basin
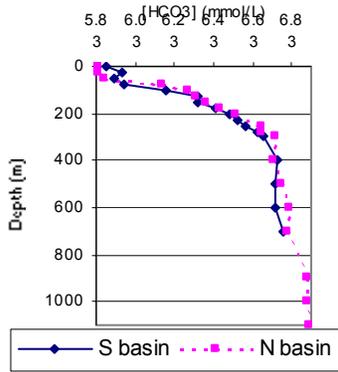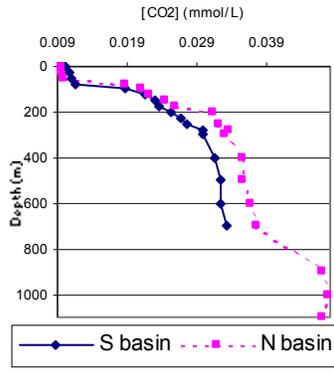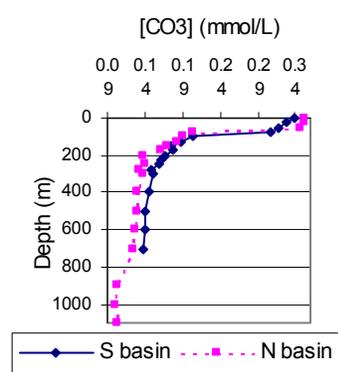
Fig. 13. Historical Temperature Profiles

Temperature (deg C)

2000 S   2000 N

Depth (m)
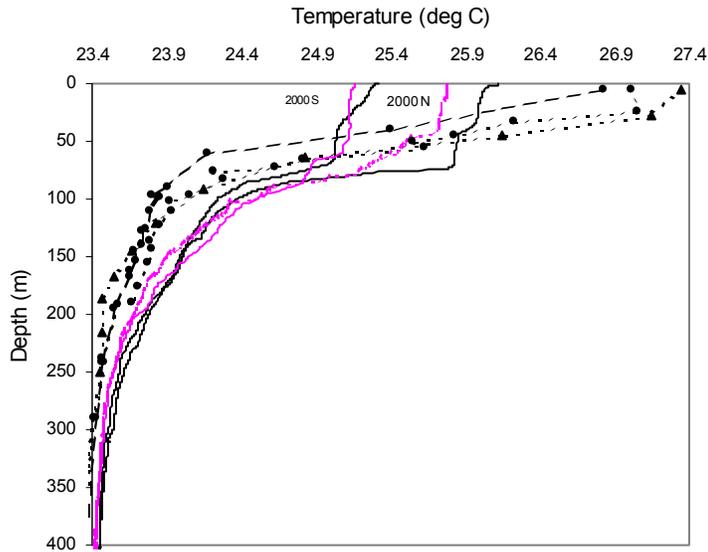
Figure 14. Seasonal Upwelling
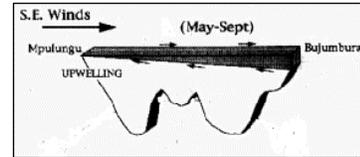
Fig. 15. Average Minimum Temperature v. Year

2001 N
2001 S
1973A N
1973B N
1973B S
2000 N
2000 S
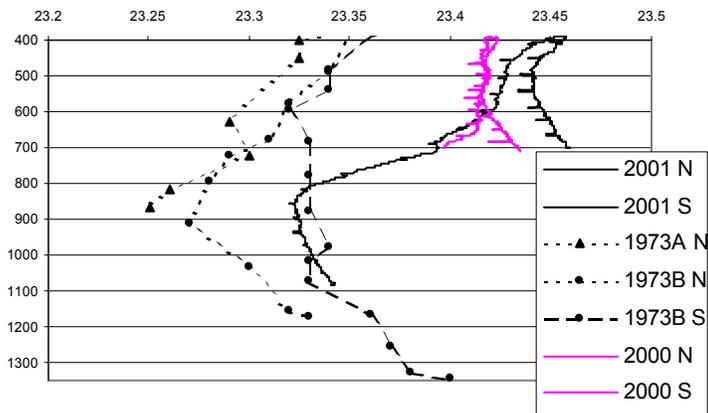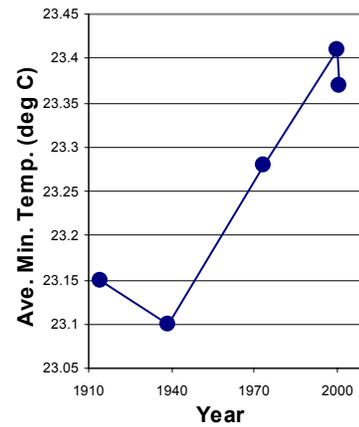
The third pattern visible in Figure 13 is a warming trend in the hypolimnion. The hypolimnion temperatures in the 2000 and 2001 profiles are warmer than those from the 1973 profiles, which are still warmer than the values from 1914 (23.15ºC) and 1939 (23.1ºC) (Edmond *et al.*, 1993) (Figure 15). The lowest temperatures in the three 1973 profiles were 23.25ºC, 23.27ºC, and 23.32ºC (average 23.28ºC), those of the 2000 profiles were 23.40ºC and 23.41ºC (average 23.41ºC), and those of the 2001 profiles were 23.31ºC and 23.42ºC (average 23.37ºC). A warming trend is evident in these data. This trend has been observed, and is probably tied to the global increase in air temperature that has been observed since the late nineteenth century (Plisnier, 1997).

The dissolved oxygen meter on my CTD could not be calibrated due to a problem with the CTD software. D.O. data taken at the same time by Wehrli and Dinkel (pers. comm.) and processed immediately using the Winkler method showed the oxycline and the beginning of the anoxic layer to be in the same place as in my CTD data, but had different values for the oxic layer. My D.O. values for surface water were 4.25mg/L north and 4.84mg/L south; theirs were 7.24 mg/L north and 7.80 mg/L south. The shape of my D.O. curve reflects the shape of the true D.O. profile, but the values in the oxic layer are too low. In both basins, there is a drop in D.O. in the top 10 meters of the water column, and the D.O. values remain relatively constant from 10m to 75m. Less oxygen is being produced in the top 10 meters of the water column because of photoinhibition. In Lake Tanganyika, the water is highly transparent. The average secchi depth during the three sampling days was 9.9m. Radiation is often so high at the surface that photosynthesis is inhibited, so the algae move to deeper water where radiation is not so strong (Jarvinen *et al.*, 1996). The oxycline is 7m deeper in the south basin than it is in the north basin. This parallels the difference in thermocline depth, and probably happens for the same reason (more mixing in the south due to stronger winds). The difference in thermocline and oxycline depth between the two basins could also have been caused by internal wave movement. From 85m to 180m, between the base of the thermocline and the top of the anoxic layer, D.O. fluctuates in both basins. This is probably due to physical processes such as turbulence, because there is no common biological process that would cause this trend (J. Scott, pers. comm.). Conductivity is higher in the surface water of the north basin than in the surface water of the south basin, and higher in the deep waters of the south basin than in those of the north basin. This pattern was also observed at the same sites last year (Adams and Charles, 2000). Conductivity decreases where organisms are present because they take up ions. The conductivity peak at 80m is at the same location as the thermocline. Plankton living in the epilimnion decrease the conductivity there, and bacteria decrease the conductivity just below the thermocline (J. Scott, pers. comm.). Perhaps there are fewer organisms living right at the thermocline than just above and below it, so ion uptake is decreased at the thermocline.

Photosynthetic organisms increase the pH of the water they inhabit by taking up dissolved inorganic carbon for photosynthesis. The pH of the surface water is the highest, and drops steeply after 50m, which corresponds to the bottom of the photic zone, which in Lake Tanganyika usually extends to about 40m (Sarvala *et al.*, 1999). The alkalinity trend I observed is also visible in 1973 data, with the lowest values at the surface and the highest values in the deepest water (Craig *et al.*, 1974). Data collected last year from the sites that I sampled show a marked decrease in alkalinity from 0m to 100m, but last year alkalinity was not analyzed until several days after collection and therefore may be less reliable than this year's data, which was analyzed immediately. A lake's alkalinity increases with its age. Lake Tanganyika is 15-20 million years old (Cohen *et al.*, 1993), and its alkalinity is high. Alkalinity increases with depth because carbon ions accumulate in deeper waters, where they are not assimilated by photosynthetic organisms. The relative concentrations of CO_2, HCO_3^-, and CO_3^{2-} are a function of pH. At Lake Tanganyika's pH (8.46 to 9.08), HCO_3^- is the dominant species. Unlike CO_2 and HCO_3^-, the concentration of CO_3^{2-} decreases as pH decreases, so it becomes less abundant in deeper waters.

In Lake Tanganyika, SiO_2 concentration normally increases with depth (Beauchamp, 1939; Craig *et al.*, 1974; Coulter, 1991; Adams and Charles, 2000). The decrease in my SiO_2 values below 600m is probably in error due to inadequate preservation of samples. SiO_2 is normally taken up by siliceous planktonic organisms, which live only in the epilimnion (Coulter, 1991).

The nitrate peak at 100m is higher in the south basin (0.11mg/L) than in the north basin (0.08mg/L). This difference was also observed at these sites one year ago (Adams and Charles, 2000). The lake's nitrogen cycle is evident in Figure 7. These data follow the trend apparent in previous research (Plisnier *et al.*,

1999). NH_4^+ is the most reduced inorganic fixed nitrogen species in the lake, and is therefore the only fixed nitrogen species that exists in the anoxic hypolimnion. Because these bottom waters rarely mix into the lake's upper layers, they accumulate high levels of ammonium. NH_4^+ is not present in the oxic layer because nitrification by the bacteria *Nitrosomas* and *Nitrobacter* at the oxic-anoxic boundary converts NH_4^+ to NO_3^-, which can be converted through denitrification to NO_2^-. An NO_3^- peak usually exists just below the oxycline (Coulter 1991). This NO_3^- peak is visible at 100m in my data. This NO_3^- peak corresponds to a decrease in NO_2^-. Below this, NO_2^- has a small peak. Perhaps this lake's nitrifying bacteria inhabit a layer just above the layer of denitrifying bacteria. Microbial communities normally exist in layers (J. Scott, pers. comm.).   Above the nitrate peak, concentrations of inorganic fixed nitrogen species are low. Several factors contribute to this pattern. Much of the nitrogen that comes up into the bacterial mats just below the oxycline does not make it into the epilimnion because denitrification can convert NO_3^- and NO_2^- to N_2, which can be lost to the system if it is not refixed. Photosynthetic organisms assimilate the nitrogen that does make it into the epilimnion (Coulter, 1991).

Conclusion

Many of the patterns evident in these chemical profiles are related to biological and physical processes. The profiles can be used to understand many of the lake's processes, such as turbulence, photoinhibition, and the nitrogen cycle. Many of Lake Tanganyika's processes can only be understood with long-term study, as is evident when my profiles are compared to historical data. The profiles I obtained contribute to a larger body of knowledge and can serve as a reference for future work.

Acknowledgements

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