A preliminary investigation of lake stability and chemical analysis of deep waters of the Kigoma sub-basin (northern basin) and the Kalemie sub-basin (southern basin) of Lake Tanganyika

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Objective

To compare the chemical and physical parameters that affect Lake stability in Kigoma sub-basin and in the Kalemie sub-basin of Lake Tanganyika with different total lake depths of 1200 and 800m, respectively.

Description

Lake stability is the amount of work needed for a water column to overcome thermal stratification, and hence vertical density differences in order to completely mix. Using knowledge of relevant mixing processes and density as a function of temperature, it is possible to show that thermal stratification results in high lake stability (no mixing); whereas, an isothermal condition causes low lake stability (complete mixing). In addition to this, deep-water nutrients (down to 700m) will be documented in order to determine the amount available for mixing into shallower waters and their relationship to physical lake stability. This is the environment of bacteria and the microbial loop. Therefore in order to more correctly assess paleolimnological data, it is necessary to understand the current physical and chemical conditions of deeper waters instead of only shallow sampling, which allows analysis of a small portion of the water column.

Introduction

Lake Tanganyika is located between 3°20’ - 8°45’ South and 29°05’ - 31°15’ East at an elevation of 773m. Its surface area is 32,600 km$^2$, maximum length 650km and mean width is 50km. The mean depth of the lake is 570m, with its maximum depth in the south basin at 1470m. The maximum depth in the north basin is 1310m and the Kalemie shoal between the two basins is 885m deep (Figure 1).

Previous stability research on the lake has focused primarily on the epilimnion (down to 150m), with few sites extending down into deeper waters. As a result, this investigation on 700m deep vertical profiles is the first of its kind in the Kalemie sub-basin. Previous researchers have hypothesised possible nutrient transport between the Kalemie Shoal and the deeper north and south basins, which are separated by shallower lake depths (Edmond et al, 1993). During the dry season (May – September), the Southeast winds tilt the thermocline northward over the entire lake. In the south basin, the oxycline is deepened as well as the thermocline, resulting in an upwelling of nutrients into the epilimnion (Coulter et al, 1991). Physical processes of mixing in the dry season include increased vertical diffusion, boundary mixing, entrainment of the metalimnion, and upwelling. The Kalemie sub-basin is particularly interesting because turbulence occurs with internal waves and probably deep currents hitting the lake bottom leading to local mixing and potentially releasing nutrients from the sediments. From this preliminary investigation of the physical parameters the following theories will be addressed:

1. That low stability is a cause of nutrient influx into the epilimnion due to mixing with waters from the hypolimnion, and

2. That stability in both basins is affected on an annual basis by wind, temperature stratification, and other seasonal changes.
Fig. 1

Fig. 2
Methods

Chemical

Sampling sites for both physical and chemical parameters in Lake Tanganyika (Figure 2) are located at S6°33' E29°49' (tested on 7/22/00) for the Kalemie sub-basin (South) and S5°5' E29°31' (tested on 7/25/00) for the Kigoma basin (North). The position of each sampling site was recorded with GPS (Global Positioning System). Water samples for chemical analysis were taken using a 5L water bottle with a simultaneous CTD cast recording the actual sampling depth. Water samples were kept in a freezer for transportation back to land, with the exception of samples used in analysis of silica, which was kept at 4°C. Turbidity was analyzed using a HACH portable turbidimeter 2100P. pH was analyzed in the field with a portable pH meter calibrated to 7 and 10 pH. Lab analysis was performed according to methods accompanying HACH DR/2010 spectrophotometer. Alkalinity was measured using titration with sulfuric acid after addition of phenolphthalein and bromcresol methyl red. Water samples were filtered before analyzing PO$_4^{3-}$, NH$_4^+$, NO$_3^-$, and NO$_2^-$. Soluble reactive phosphorus was measured using the ascorbic acid method; Nitrate was analyzed using the cadmium reduction method. Ammonium was measured with the salicylate method for low range ammonium. Silica was analyzed with the silicomolybdate method for high range and using the heteropoly blue method for the low range. Interference in the methods included H$_2$S at any level for the determination of phosphorus and a highly buffered (alkalinity) sample may interfere with the determination of nitrate. The CTD also recorded parameters of pressure, depth, temperature, conductivity, and dissolved oxygen every 0.5 seconds.

Physical

Using density as a function of temperature (down to 700m), four mathematical calculations related to lake stability were completed for both the north and south basin. A stratification index (SI) was measured using the standard deviation of the density matrix. The stratification index is a way to quantify thermal stratification; a high stratification index represents intense thermal stratification and high stability, whereas a low SI indicates very little stratification and low stability. The index was calculated for the north and south basin using two different methods: first using temperatures received per meter from 0m to 700m, and second using data at 10 meter intervals from 0m to 100m. The latter method was used in order to compare with previous stratification index data (Plisnier et al, 1996: FAO report). We also calculated the Wedderburn Number (W), which utilizes wind speed, ratio of epilimnion depth to overall lake depth, density of the epilimnion and hypolimnion, total lake length, and gravity.

\[
W = \frac{g h_e^2}{\mu_L} \quad g' = \frac{2(\rho - \rho_e)}{\rho} \quad (\text{Monismith, 1983})
\]

This dimensionless parameter is a measure of the effect of wind stress on the lake surface. There are four major classifications for the Wedderburn number:

1. \( W > \frac{L}{4h_e} \) - strong thermal stratification, little mixing, small internal seich amplitudes.

2. \( \frac{1}{2} < W < \frac{L}{4h_e} \) - wind induced mixing stronger than thermal stratification, more surface mixing than instability at the thermocline, large internal seiche amplitudes.

3. \( \frac{h_e}{L} < W < \frac{1}{2} \) - higher degree of mixing between the epilimnion and hypolimnion, much upwelling at the thermocline (unstable) surface at the upwind end of the basin.

4. \( W < \frac{h_e}{L} \) - complete overturn (mixing).
The Brunt Vaisala frequency (buoyancy frequency N) was measured using gravity, the average density for the entire depth measured, and the vertical density gradient in each basin.

\[ N^2 = -\frac{g \phi}{\rho \frac{\partial \rho}{\partial z}} \]  
(Brunt Vaisala Frequency) (Moritmer, 1974)

This is a measure of the work that must be done against gravity in order to break down thermal stratification in the water column. Previous research of buoyancy frequency in Lake Tanganyika has only been calculated using data from 150m. As a result, N was determined for both the north and south basins in two separate profiles: down to 700m and down to 150m. An equation for total lake stability was computed using the Schmidt 1928 version. This calculation required use of surface area, area at each depth measured, gravity, the depth to the center of gravity for a stratified lake, total lake volume and the density at each meter.

Variables

**Wedderburn Number**

- \( h_e \) = height of epilimnion (m), \( \mu_* \) = shear velocity of water at surface (m/s), \( L \) = length of the lake (m), \( \rho \) = density, \( \rho_e \) = average density of the epilimnion, \( \rho_h \) = average density of the hypolimnion, \( g \) = 9.8 m/s

**Buoyancy Frequency**

- \( \rho \) = average density of depth measured, \( \frac{\partial \rho}{\partial z} \) = the density gradient

**Stability**

- \( A_0 \) = surface area of lake (cm\(^2\)), \( z \) = depth (cm), \( z_m \) = maximum depth (cm), \( z_0 \) = first depth (cm), \( A_z \) = area at depth \( z \) (cm\(^2\)), \( \rho_z \) = density at depth \( z \), \( V \) = lake volume (cm\(^3\)), \( z_g \) = depth to the center of gravity of stratified lake (cm).

Results

**Nutrient Profiles (H. E. Adams)**

The temperature profiles between the two sites are very similar. The south basin profile is slightly cooler at the surface, 25.15°C and declines more sharply than the north basin, which has a surface temperature of 25.78°C (Figure 3). Both locations have a bottom temperature of 23.4°C. The dissolved oxygen shows a similar trend with the oxycline at 90m and the anoxic layer (DO= 0mg/L) approximately 150m deep in both locations. Conductivity, soluble reactive phosphorus, and soluble silica all increase with depth (Figures 4,5,6). Conductivity ranges from 664 to 682 S/cm in the south basin and 668 to 683 S/cm in the north, with a decline to 665 S/cm at 80m. Phosphate in the north basin increases from 0.02 mg/L to 0.27 mg/L at a shallower depth than the southern basin, which increases from 0.03 to 0.25 mg/L. Silica in the north basin (1.293 to 13.5 mg/L) continues to increase with depth, more than in the south basin (1.35 to 12.4 mg/L). Nitrate shows a peak above the metalimnion and is at a higher concentration in the south basin (Figure 7). In the north basin, nitrate ranges from 0 to 0.66 mg/L and in the south basin it ranges from 0.015 to 0.089 mg/L. Ammonia remains at low levels until below the anoxic layer and increases at a shallower depth in the north basin (Figure 8). In the north basin it ranges from 0 to 0.44 mg/L and in the south basin from 0 to 0.42 mg/L. Nitrite remains at low levels in both profiles, 0.010 to 0.015 mg/L in the north and 0.011 to 0.015 mg/L in the south, with slight increases in the hypolimnion of both basins (Figure 9).

The largest differences between the two basins are seen in turbidity, pH, and alkalinity. Turbidity increases dramatically from 0.13 to 0.58 NTU with depth in the south basin while remaining below 0.19 NTU in the north basin (Figure 10). Alkalinity in the north basin ranges between 5.48 and 5.86 mEq while the south basin had slightly higher values between 5.58 and 5.96 mEq (Figure 11). The pH is lower in the south basin with values between 7.88 and 8.31 in comparison to the north basin that has values between 8.24 and
Figure 12. pH Profiles.

Figure 13. Total dissolved inorganic carbon (DIC) profiles, calculated from temperature, alkalinity, and pH.

Figure 14. Bicarbonate (HCO3) profiles, extrapolated from temperature, alkalinity, and pH.

Figure 15. Carbon dioxide (CO2) calculated from temperature, alkalinity, and pH.

Figure 16. Carbonate (CO3) extrapolated from temperature, alkalinity, and pH.
8.56 (Figure 12). Calculated carbon forms are mostly bicarbonate, with the south basin showing a higher total dissolved inorganic carbon, $\text{HCO}_3$ and $\text{CO}_2$ concentrations overall (Figures 13, 14, 15). The north basin has a higher concentration of $\text{CO}_3^2-$ throughout the sampled water profile (Figure 16). The nitrogen to phosphorus molar ratio (Figure 17) varies in the epilimnion, higher in the south basin but still below 11. The silica to phosphorus ratio is generally above 16 and the silica to nitrogen ratio varies from 4 to 20 (Figures 18, 19). The north basin shows more variability above 200m; however, both sites show a dampening in the ratio variability with depth. Dissolved carbon dioxide, calculated from alkalinity, pH and temperature, shows a carbon to nitrogen ratio above 12 in the metalimnion and epilimnion and approximately 4.8 to 6 in the hypolimnion of the south basin; the north basin has a carbon to nitrogen ratio of above 7.9 in the epilimnion and below 4.3 in the hypolimnion (Figure 20). As seen in Figure 21, the carbon to phosphorus ratio is well below 100 in both the north and south basin, with the exception of the epilimnion in the south basin.

**Physical Analysis (R. M. Charles)**

**Stratification Index (SI)**

$$SI = Sdi \times 10^4$$

$Sdi$ is the standard deviation of the density profile.

In Kigoma Bay the Stratification index was 1.76 for 700m, and 1.21 for 100m (second method). For the Kalemie sub-basin the index was 1.39 for 700m, and 0.56 for 100m (second method).

**Wedderburn Number (W)**

The results from both the north and south basin fit the third classification. \( \frac{h}{L} = 6.15 \times 10^{-5} \) in Kigoma bay

\[ W = 0.046, \quad \frac{h}{L} = 8.0 \times 10^{-5} \] in the Kalemie sub-basin where \( W = 0.0455 \) (Figure 22).

**Buoyancy Frequency (N)**

For Kigoma bay, \( N^2 = 3.1 \times 10^3 \text{ sec}^{-2} \) for 150m, and \( N^2 = 8.4 \times 10^4 \text{ sec}^{-2} \) for 700m. For the Kalemie sub-basin, \( N^2 = 1.8 \times 10^5 \text{ sec}^{-2} \) for 150m, and \( N^2 = 6.1 \times 10^6 \text{ sec}^{-2} \) for 700m.

**Stability (S)**

\[
S = \frac{g}{A_0} \int_{z_0}^{z_e} A_1 (1 - \rho) (z - z_0) dz
\]

(measured in Ergs: g-cm cm$^{-2}$) (Schmidt, 1928)

Stability is the amount of work needed to be done by the wind for a water column to overcome thermal stratification, and hence vertical density differences in order to completely mix. This stability equation (Schmidt 1928) is intended to produce a number for the lake as a whole. As a result, using the appropriate variables needed, the result for both the north and the south is very close. Stability for the south is $3.384 \times 10^6$ g-cm cm$^{-2}$, and stability for the north is $3.386 \times 10^6$ g-cm cm$^{-2}$. In order to do a true investigation of overall lake stability using this equation, temperature profiles should be conducted down to the deepest depth at several locations in the Lake. An average of the temperature data should be calculated in order to receive one number for the whole lake. Stability increases as the lake becomes more stratified.

**Discussion**

**Nutrient Profiles (H. E. Adams)**

The temperature profiles for both sampling sites show stratification typical of a tropical lake in the dry season. Stratification is generally at its lowest this time of year, although a significant density difference still exists (Coulter, 1991). Between the two basins, the site in the Kalemie sub-basin shows a weaker thermocline, leading to weaker stability. The thermocline location and strength, along with the anoxic boundary, control the location of most chemical parameters. Most organisms live in the epilimnion, allowing an accumulation of nutrients where they are not accessible for uptake. The oxicline, located at
Figure 17. Molar Ratio of Nitrogen to Phosphorus.

Figure 18. Molar Ratio of Silica to Phosphorus.

Figure 19. Molar Ratio of Silica to Nitrogen.

Figure 20. Molar Ratio of Dissolved Carbon Dioxide and Dissolved Inorganic Nitrogen.

Figure 21. Molar Ratio of Carbon Dioxide and Dissolved Inorganic Phosphorus.
approximately the same location in both basins, is much shallower than is found in other water masses with similar depths. As a result, the majority of the water column is anoxic, trapping a large amount of nutrients and allowing a much larger habitat for anaerobic bacteria.

The high conductivity increases with depth due to increased ions (nutrients) in the water column, particularly below the thermocline. The south basin shows a larger increase in conductivity from surface to depth while the north basin shows an additional decrease at the thermocline where the autotrophs take up ions for use in photosynthesis at very low light levels or chemosynthesis. The north basin also has a continued increase in conductivity below 300m, whereas the south basin approaches a vertical asymptote. Due to the north site’s deeper total lake depth, it can be hypothesized that conductivity continues to increase below 700m.

Soluble reactive phosphorus has an increase with depth that also coincides with the thermocline and anoxic layer. The north basin shows an increase in SRP at a shallower depth probably due to a more stable thermocline. The south basin, in the dry season, is affected by the south to north winds which tilt the thermocline and weaken stratification, allowing a vertical upward flux of phosphorus across the thermocline, where it can be taken up by organisms (Hecky et al, 1978). The deeper water samples in the north basin again suggest that there are higher phosphate values below 700m. The soluble silica (silicic acid) in the water column follows a similar trend, with slightly higher values in the north basin near the thermocline, where the Si:P ratio is high and the phytoplankton could be phosphorus limited. However, most of the nutrients could be stored in organisms and molar ratios in the water column are just indicative of nutrients available, not including quick turnover from organismal release.

The nitrogen at the two sites basically follow the trend seen in previous research (Plisnier et al, 1999) with a nitrate peak highest in the epilimnion, ammonium increasing in the hypolimnion, and nitrite remaining at low levels. However, the amplitudes of the nitrate and ammonium peaks differ between basins. The north basin shows peaks that are distinctly separated by the thermocline and anoxic layer with a fixed nitrogen minimum that, according to Rudd (1980), is a result of denitrification between 160 and 200m water depth. The south basin has a higher concentration of nitrate in the epilimnion and also decreases more slowly than the north basin, below the anoxic layer. This could be due to either N-fixation by cyanobacteria, less denitrification, or an upward flux of nitrogen from the hypolimnion. Previous researchers have suggested that an N-flux across the thermocline would not be possible due to rapid uptake by denitrifiers at the anoxic boundary (Hecky et al, 1991). However, because stability is low, if the nitrogen fluxes are high enough, the increased nitrate concentration in the south basin could be due to such a flux. The south basin also shows an ammonium concentration that increases slower with depth, in comparison to the north basin. This difference has been noticed previously (Hecky et al, 1978 and Edmond, 1993) but ammonium to nitrate conversion across the oxycline has not been monitored over a long series of observations.

Turbidity is very different between the two sites. Both basins have low turbidity, characteristic of oligotrophic lakes, although the south basin shows an increase with depth that exceeds the highest values found in the north basin. This difference could be indicative of the basin morphology. The southern Kalemie sub-basin is located next to the headlands of the Mahale Mountains. With the southern winds, the lake currents would be much faster and cause turbulences and local mixing at this location. Entrainment of sediments would account for the increased turbidity in the south. This place is well known for its high wave activity (TAFIRI, personal communication).

Alkalinity is found at high levels and follows the same trend in both locations. In the epilimnion, alkalinity decreases due to carbon uptake by autotrophs and increases again below, in the hypolimnion. The south basin has higher alkalinity at the surface and in deep waters probably because of different watershed inputs. The pH difference between the two basins also follows similar trends to each other, with decreasing pH with depth until an increase at 700m, which may continue to increase deeper. The higher pH in the north could be due to nocturnal activity of bacteria, previously suggested (Plisnier, personal communication), accompanying lake-wide oscillations or different water masses. Dissolved inorganic carbon has a higher concentration overall in the south basin, with the same trend as alkalinity. Higher bicarbonate and carbon dioxide concentrations in the south basin would allow for easier uptake and conversion by autotrophs. The
higher concentration of carbonate in the north basin is harder for organisms to convert into usable carbon dioxide.

Molar ratios suggest that nitrogen is the most limiting nutrient in the water column, and then phosphorus. However, if the main autotrophs in the water column are cyanobacteria, there would be a large amount of biological fixation, resulting in a nitrogen flux into the lake. Phosphorus availability is dictated by the amount of nutrient flux across the anoxic layer and would vary the most with stability. In the south basin, lower stability allows a weaker thermocline, which phosphorus can cross easier, providing cyanobacteria with the main nutrient required. The seeming lack of silica limitation in the ratios is important for diatom abundance, which would compete with cyanobacteria for light and nutrients when not nitrogen limited.

**Physical (R. M. Charles)**

**Stratification Index**

There is a greater stratification index in the north than there is in the south probably because of the effects of the dry season (July). The results for this year are similar to those of 1996. At Kigoma the SI was 0.8, and the values from Kigoma to Mpulungu range from 0.2 to 0.8. The result for the south basin (0.56) is indicative of the central location of the Kalemie shoal. This stratification index should be in between 0.2 to 0.8. It is possible that the stratification index for 1996 is lower because it was a colder year with less thermal stratification. The stratification indices for the north and south basin this year indicate upwelling in the extreme south that forces colder water from the hypolimnion to be mixed with warmer epilimnetic water. As a result, the thermocline at the south basin is weakened and stratification is lower than in the north where a stable and deep thermocline (100m) exists (Figure 3). Night cooling is also expected to be more important in the south during the winter of the southern hemisphere. This causes increased daily overturn of epilimnion waters and decreases the stratification.

**Wedderburn Number**

Wedderburn values below 0.5 occur during periods when mixing between the epilimnion and hypolimnion are likely. Both results for the north and south basin that fit into the third classification are indicators of a large amount of mixing between the epilimnion and the hypolimnion near the south end of the lake where upwelling occurs and night cooling (Figure1). At the south basin the thermocline is unstable due to winds from the southeast. The Wedderburn number for the south basin is less than the north because the south basin is more affected by the dry season winds, upwelling and turbulence caused by mixing. The northern end; however, has a deep and more stable thermocline. Since the Wedderburn number depends on the depth of the thermocline, temperature and density differences between the epilimnion and the hypolimnion, it is indicative of an overall temperature increase in the lake from south to north. This is due to upwelling of cold water from the hypolimnion and night cooling at the south basin.

**Buoyancy Frequency**

The buoyancy frequency in the north is higher than in the south as a result of stronger thermal stratification in the north (Figure 3). This equation is usually estimated locally. Due to upwelling and much turbulence in the south, the temperature and density gradients are not as strong as they are in the northern end of the lake. In addition to this, the morphology of the Kalemie sub-basin involves complex shallow escarpments, a narrow width, and a shorter depth (885m)(Figure 23). Therefore, turbulence is expected to be more significant in the Kalemie sub-basin due to wind vortices in relation to the Mahale Mountains, and interactions of water with the sediment. Graphically, the buoyancy curves for both basins show an increase to maximum stability at the thermocline and then a decrease asymptotically approaching zero (Figure 24). The curve for the north basin is more steady due to the higher stratification and more stable thermocline that in the Kalemie sub-basin. The curve for the south basin is not as sharp because the thermocline begins to destabilize from mixing.
**Stability**

The stability of the lake fluctuates with seasonal changes and the annual limnological cycle (Plisnier et al., 1999). In May-June, the southeast winds force warm water from the epilimnion northward resulting in a deep thermocline in the north. Colder water and nutrients from the hypolimnion are mixed with epilimnetic water in the south basin. This turbulent action breaks down thermal stratification. As a result of this and mixing from increased cooling during the night in the south, the thermocline becomes unstable and stratification decreases from north to south. During this season, lake stability should theoretically be low $(3.38 \times 10^4 \text{ g-cm}^2 \text{cm}^{-2})$. When the southeast winds cease in September, the metalimnion oscillates until it gets back to an equilibrium level. At this point in time overall lake stability should be higher due to a lack of upwelling, and lack of strong winds. At this time there is also increased radiation from October-November (southern summer). Despite internal oscillations, thermal stratification should be higher than in the dry season. During October-November secondary upwelling in the north moves deep water upward as in upwelling during May-July in the south. The strong surface waves (‘Chimbanfula’) that are experienced near Mpulungu in October (Plisnier et al, 1999) could cause stability to decrease. The end of these strong waves marks the beginning of the wet season where stratification and turbidity increases (February-May). During February-May stability should be increasing to a maximum. Lake stability then begins to descend as the wet season ends and the dry season begins. The annual limnological/stability cycle continues (Figure 25). As a result, the July 2000 stability calculation is an indicator of a low stratification as compared to the general stability of the wet season. The stability value also shows that stability for the lake increases with depth. The farther down data is collected, the more water and pressure there is. Thus it takes more work to raise this mass. There are no published calculations of this particular stability equation for Lake Tanganyika. Therefore a comparison of the July 2000 result is not possible. Further deep water testing and calculations must be conducted at different locations of the lake (and monthly) in order to fully understand an annual stability cycle. Also the average temperature for each depth should be calculated and used in this equation in order to quantify the stability of the lake as a whole.

**Conclusion**

The Wedderburn number, stratification index, buoyancy frequency and stability (Schmidt, 1928) equations all show that the overall stability of the lake is low during the dry season. From the southeast winds, turbulence, upwelling and other seasonal effects, the south basin is less stable than the north basin. In fact, night cooling is a more important factor of less stratification in the Kalemie shoal, rather than upwelling in the far south. Testing at the northern end (July 25, 2000) was conducted at night; whereas, the southern testing was conducted during the day around 12pm (time of maximum irradiance). As a result, the temperature stratification in the north was not as strong as it would have been during the daytime. If both of the sites had been tested during the day at the same time, there would have been a larger difference in the results for the north and south in each mathematical equation. The conclusion of overall low lake stability causes nutrients such as nitrate, phosphorus and silica to diffuse across the metalimnion. Nitrate in the south basin is probably increased by a large flux from the hypolimnion. Nitrogen dynamics should be further investigated by examining Nfixation in the epilimnion, denitrification in the metalimnion, and autotrophic populations throughout the water column. The increased dissolved inorganic carbon in the south basin is indicative of the geological factors affecting water masses in the different sub-basins. The Kalemie sub-basin wind-induced currents are controlled not only by regional wind patterns, but also largely by the Mahale Mountains offshore-inshore winds. Turbidity should theoretically be higher in the south basin as opposed to the north because of the turbation of sediments and local upwelling. The annual limnological cycle should correlate with changes in stability and various nutrient fluxes (chemical variations) into the epilimnion.

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