CHAPTER SIX

Hydraulic conditions of the Ugandan portion of Lake Victoria

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ABSTRACT. *Hydraulic conditions (including temperature, water velocities, oxygen concentration and Secchi depths) of the Ugandan portion of Lake Victoria were studied from 1999 to 2005. This information was augmented with data from other sources to compile a record extending from 1994 to 2005. Influents from River Kagera into Lake Victoria were studied on a monthly basis. The temperature distribution profiles on the eastern part of the lake showed similar patterns to the historical observations. Water column temperatures and stratification are very prominent in the months of February, March and April in the entire Ugandan portion of the lake. The western part of Lake Victoria is much influenced by wind forces and therefore experiences more mixing and cooling patterns. The eastern part of Lake Victoria is much more influenced by thermal stratification patterns and therefore mixing is mainly due to density currents. The eastern part of Lake Victoria experiences higher water temperatures throughout the year due to a lower rate of light penetration and weaker mixing.*

Keywords: Oxygen Distribution, Secchi Depths, Seiches, Thermal stratification.

INTRODUCTION

Nutrients are re-suspended into the photic zone from the nutrient-rich deeper waters of lakes through mixing (Schladow et al. 2004). Even though dissolved nutrients are assimilated rapidly in the photic zone, recycling and retention of nutrients can result in chemical and biological effects that are spatially and temporally dissociated from a vertical mixing event. Thus, it is necessary not only to determine the vertical transport of nutrients but also the horizontal transport of matter in the photic zone.

Vertical transport of nutrients is carried out in two major ways, namely, by upward flow (or upwelling) and by water turbulence. The latter may further be classified into down gradient transport due to the weak turbulent mixing in the interior of the water column and vertical entrainment of higher nutrient concentrations into the near-surface mixed layer (Jo 1973).

In lakes, the transport processes of particulate and dissolved constituents in water are related to water motion and currents that are induced by several factors, including the following: river (or stream) inflow and outflow into and out of a lake respectively; secondly, wind induced currents, including wave motion and the pulsating turbulent motion caused by seiches (wind set-up). Also, density currents (in deep thermally stratified lakes) transport particulate and dissolved matter in water (MacIntyre *et al*. 2002; Schladow *et al*. 2004).

Differential heating and cooling of surface waters, as well as influents, can cause convectional currents. However, mixing of surface waters by convection is weak and insufficient to produce long-term stratification patterns commonly observed in most lakes. Wind energy mechanically distributes most of the heat in a lake. During warmer periods of the year, the surface waters are heated, largely by solar radiation, more rapidly than the heat is distributed by mixing. As the surface waters are warmed and become less dense, the relative thermal resistance to mixing increases. The lake becomes stratified, and will have three distinct zones: epilimnion (an upper stratum of less dense, more or less uniformly warm, circulating, and fairly turbulent water), hypolimnion (the lower stratum of more dense, cooler and relatively quiescent water lying below the epilimnion) and the metalimnion (the transitional stratum of marked thermal change between the epilimnion and hypolimnion). The thermocline (a change > 1^{o}C/m) is the plane or surface of maximum rate of decrease of temperature in the metalimnion (Azza *et al.* 2001).

If water in a lake is heated rapidly and wind induced mixing of water is intense but insufficient to circulate the water from top to bottom, the stratum of greatest thermal change will occur in the deep part of the water column. In contrast if the weather is calm and hot, strong thermal discontinuities will occur near the surface.

Movement of wind over water sets the water surface into an oscillating motion, referred to as progressive or travelling surface waves. The surface waves move in a cycloid path. Water is displaced upward and returns to equilibrium by gravity along a circular path. The height of the vertical oscillation is attenuated rapidly with depth, and decreases by half of the cycloid diameter for every depth increase of 1/9 of the wavelength. In deep waters, while water entrained in surface waves oscillates considerably up and down, horizontal movement is small as the wavelength is much less than water depth. It should be noted that the highest surface waves on a lake is proportional to the square root of the fetch, that distance over which the wind has blown uninterrupted by land.

When surface waves occur near the shore in shallow waters, their cycloid motions are transformed into a to- and fro- slashing motion that extends to the bottom of the water column. As deep water waves enter shallower water, their velocity decrease proportionally to the square root of depth. A reduction in wavelength occurs with a marked increase in wave height. With increased height the waves become asymmetrical and unstable. Shallow water wave energy is effective in moving littoral sediments to deeper waters and inhibiting the growth of many organisms not adapted to such turbulence (MacIntyre *et al.* 2002).

Langmuir circulations are large currents of turbulent waters in the upper strata of lakes that are organised into vertical helixes. Wind energy is converted through surface wave energy into turbulence; surface instability is then dispersed downward which in turn drives the water currents. Langmuir circulations move water and entrained particles in circular cells along cylindrical patterns both vertically and in a helical manner parallel to the wind direction and perpendicular to the lines of surface waves (Wetzel 1983). Downward movement velocities at cell convergences are about three times greater than upward current velocities that occur at divergences and these results in aggregation of surface particles at lines of convergences, forming streaks sometimes.

In the absence of sufficient surface cooling, wind mixing alone does not normally achieve complete isothermy – although complete vertical mixing may occur, horizontal density gradients will remain, and when the wind ceases, these will reversibly adjust under gravity to re-establish vertical stratification. The final stratification will be weaker than the initial one that existed at the onset of the wind. The amount of mixing that occurs due to a given wind force depends largely on the strength of the applied wind stress relative to that of the forces of buoyancy that are associated with stable density stratification that resists the wind-induced vertical motions.

Wind stress on water surface generates turbulence that cause mixing in the surface layer, leading to the deepening of the thermocline by entrainment of metalimnion and hypolimnion water into the epilimnion. Also, wind stress generate horizontal currents and long waves that distort the thermocline, tilting it downward and bringing warmer surface water toward the leeward end of the lake. At the windward end of the lake, the thermocline rises, bringing with it colder upwelling water from depth. Thermocline tilting thereby creates horizontal density gradients with surface layer temperatures increasing down-wind.

The strength of density stratification may be sufficient to influence water movements and the distribution of oxygen and nutrients in some lakes (Langenberg *et al.* 2003). Density differences arise mainly from temperature gradients caused by absorption of solar radiation (MacIntyre *et al.* 2002). It is believed that dissolved salts are present in Lake Victoria in sufficient amounts to influence absolute water density, but generally do not exhibit sufficient vertical variation to significantly affect vertical stability due to density differences in the water column. The Equator passes through Lake Victoria, so none of the phenomena due to Coriolis forces are expected to exist, e.g. Kelvin waves, Ekman spirals and rotating seiches (Osumo 2001).

The objective of this study was to determine the spatial and temporal variation of thermal stratification and wind driven water currents in the northern portion of Lake Victoria, and subsequently, compare and contrast the present day stratification and hydrodynamic regime with historical observations.

MATERIALS AND METHODS

Nine littoral and ten pelagic stations were established in the Ugandan portion of Lake Victoria (Figure 1). Monthly measurements of temperature and current profiles, wind speeds and directions were made from five littoral and four pelagic stations in the northern portion of Lake Victoria from 1997 to 2004. At quarterly intervals, measurements were made on nine littoral and ten pelagic stations. Additional data from previous studies was collected and a set of data ranging from 1994 to 2005 was studied. Current velocities were made with an Acoustic Doppler current profiler (ADCP), temperatures were measured using a Hydrolab multi-parameter sensor, and wind speeds and direction were measured using a digital anemometer. From 2001 to 2002, more intense measurements were carried at stations UP8 and UP6 using two ADCPs and Brancker loggers measuring at 30 minutes intervals.

RESULTS AND DISCUSSIONS

General trends of hydraulic forcing mechanisms

Solar radiation patterns

The solar radiation patterns over the lake as measured at Bukasa Island station are presented in Figure 2. It can be seen that there are marked periods of low and high solar radiation over the lake. January to March and September to October experience high values of solar radiation while April to October and November to December are periods of low solar radiation.

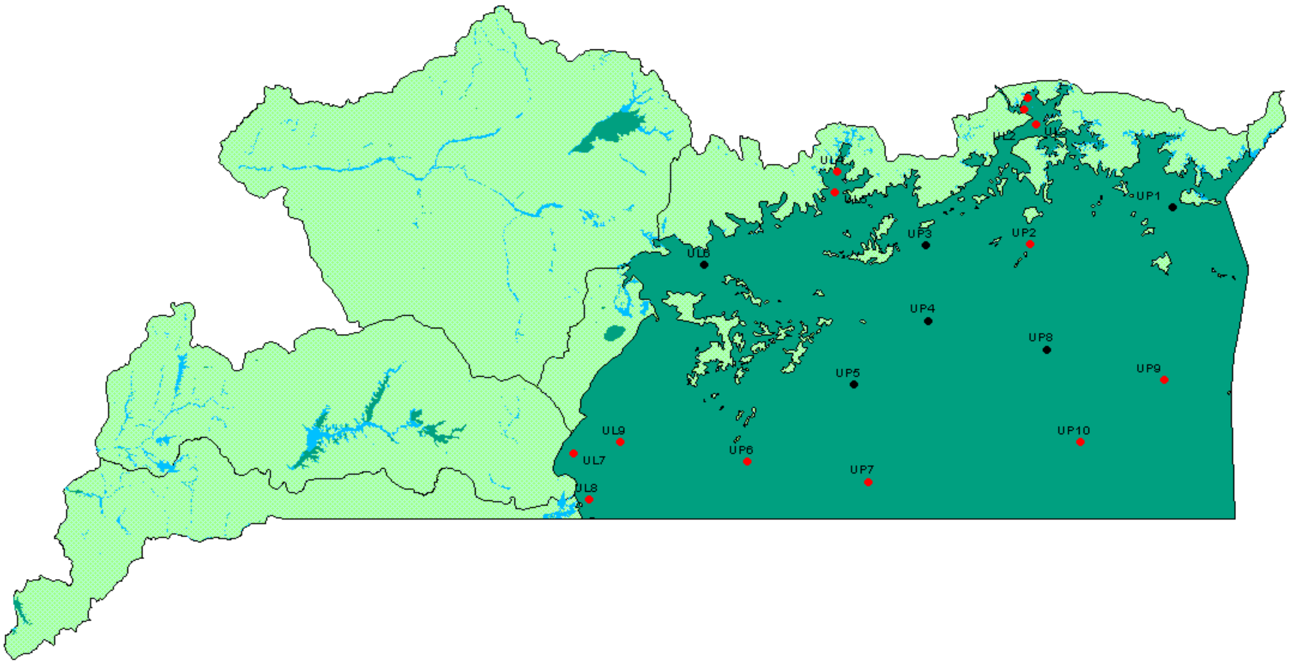

FIG. 1. Lake Monitoring Stations in Uganda, LVEMP.

Thermal stratification in Lake Victoria

Temperature profiles at Bugaia Island (UP2) 1960-61

Figure 3 adopted from Talling (1966), shows the development of the temperature profile at Bugaia Island during 1960-61. Talling described the development in three phases:

Phase 1: September to December, there is a gradual warming of the water column, with heat slowly dispersing from the surface to the bed. There are no strong thermoclines, but more of a gradual decrease in temperature from the surface downwards.

Phase 2: January to May, a thermocline develops at depths about 40 m. It was however absent on two occasions, perhaps due to the tilting of the interface across the lake so that the surface waters occupied the full depth. The surface temperature reaches a maximum in March, after which cooling starts.

Phase 3: June to August, cooling and almost complete mixed water column is observed. Other studies by Fish (1957) and Newell (1960) indicate that full mixing can also occur in January, and there is some speculation as to whether this mixing is due to oscillations of the interface across the lake or other factors.

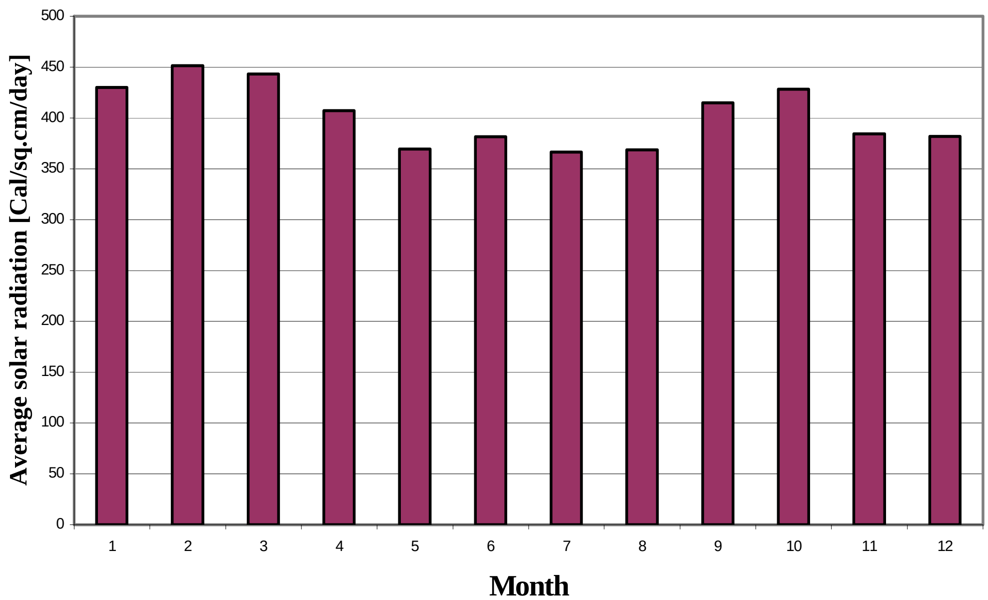

FIG. 2. Monthly average solar radiations at Bukasa Island (1972 –2004).

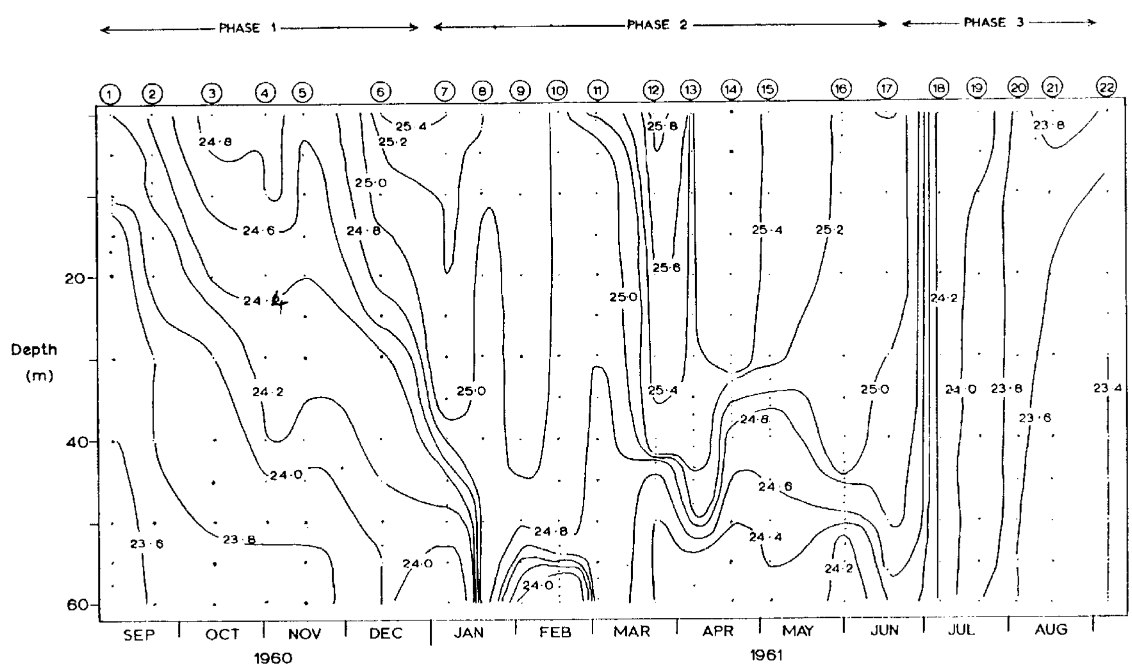

FIG. 3. Time series of temperature profiles at Bugaia Island (UP2) 1960-61, adopted from Talling (1966).

Temperature profiles at Bugaia Island (UP2) 1994-95

Temperature profiles at Bugaia for periods May 1994 to May 1995 are presented in Figure 4. In comparison to Talling's observations (Figure 3), it can be seen that the general pattern of temperature changes is similar (Hecky *et al.* 1994; Wanink and Kashindye 1998). There is a continuous cooling to a nearly mixed water column between July to the beginning of September. Then there is gradual warming and weak stratification of the profile between September and November. This is followed by the development of a strong stratification and warming in February to March, starting from the surface moving downwards.

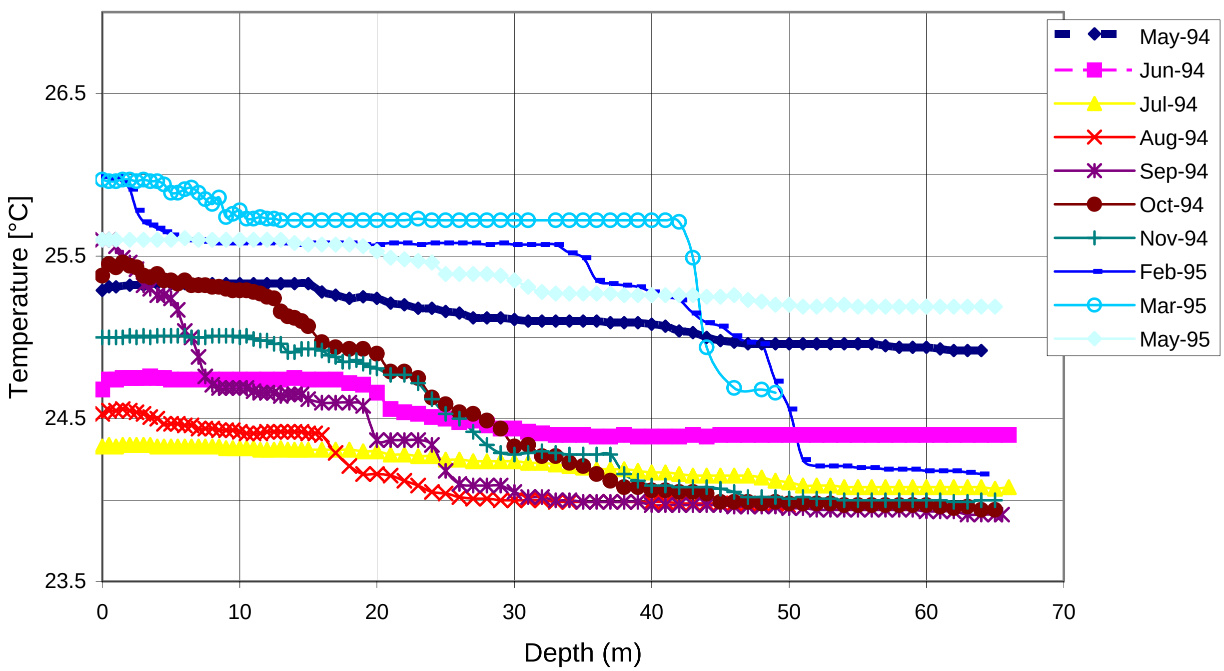

FIG. 4. Time series of temperature profiles at Bugaia Island (UP2), May 1994- May 1995.

Figure 5 shows the temperature profiles for station UP8 from November to December, 2001 while Figure 6 presents temperature profiles for station UP8 from March to May 2002. At station UP8, a strong thermocline as deep as 40m is seen between February to May and October to November. An even temperature gradient from surface to bottom without any definite thermocline is seen from beginning of December to early February. The water column is almost fully mixed for the remainder of the year.

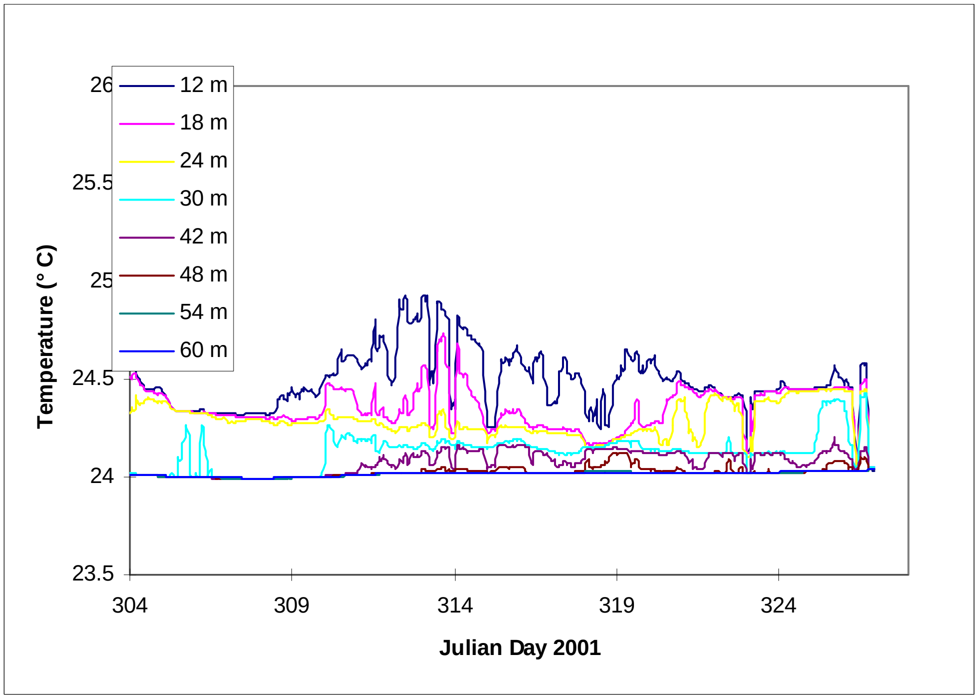

FIG. 5. Temperature profiles for station UP8 November – December 2001.

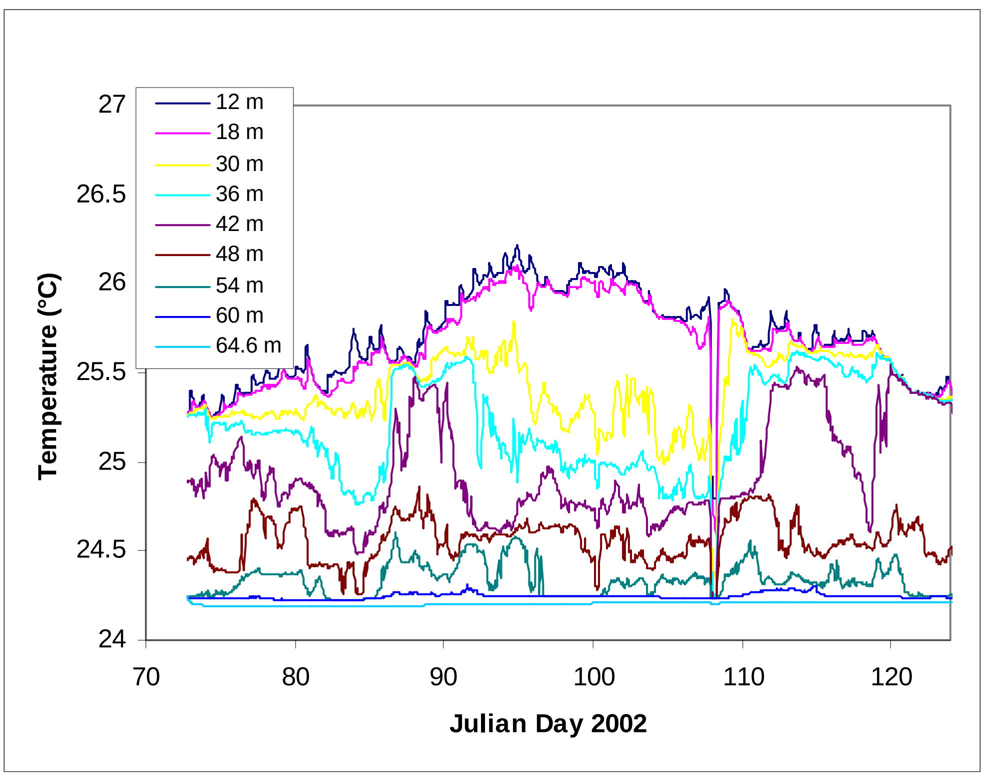

FIG. 6. Temperature profiles for station UP8 from March to May 2002.

Figure 7 presents time series of temperature profiles at UP6 from 2000 to 2001. At station UP6, there was a significant temperature gradient from February to May but remained mixed for the rest of the year. Examination of the temperature profiles for littoral stations shows no significant variations in temperature along the water column. A typical example is presented in Figure 8. However there is a general variation in the entire water column over the months and maximum temperatures are observed in March, while August experiences minimum temperatures. This temperature variation follows the variations that are observed in the solar radiation patterns.

Secchi Depths

Light attenuation feature of water to some extent influences stratification in a lake (Hocking and Straskraba 1999). All other factors being equal, a lake in which light is attenuated rapidly will have a shallower and warmer mixed layer than one in which light penetrates to greater depths, until the mixed layer depth exceeds the 5% light level. Figure 9 presents a map of Secchi depth for the littoral station from August to September 2000. Compared to the central areas of the lake, the areas closer to the shores had a thinner layer of warm water at relatively higher temperatures. This difference becomes more pronounced as one moves to the north east of the lake.

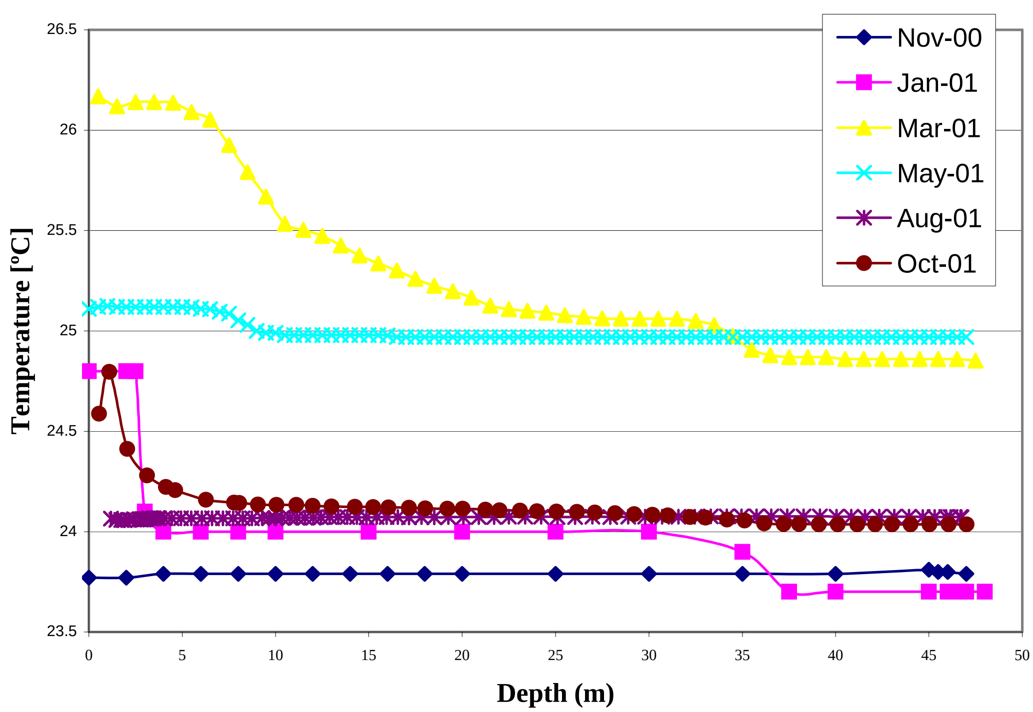

FIG. 7. Time series of temperature profiles at UP6, 2000-2001.

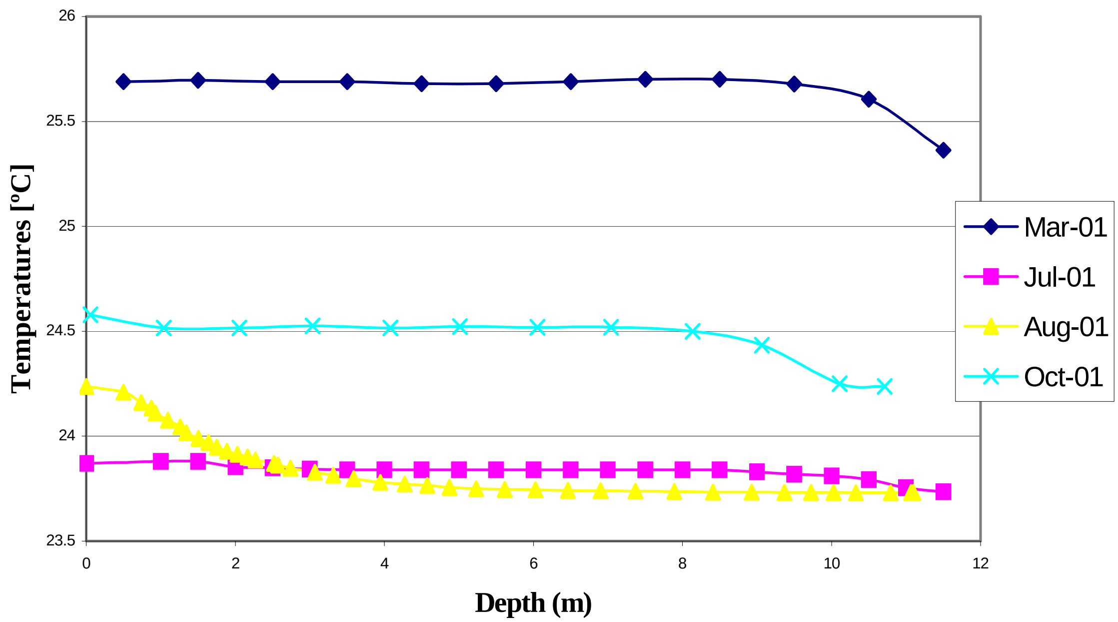

FIG. 8. Temperature profiles at UL8.

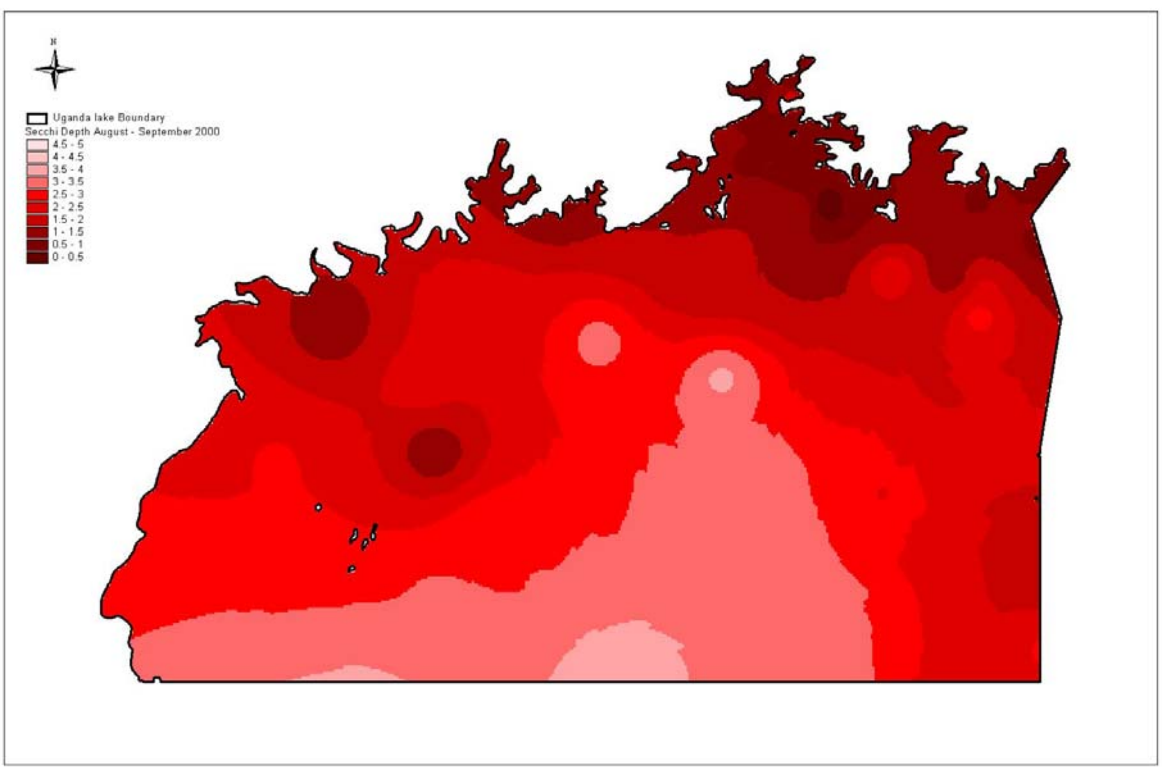

FIG. 9. Map of Secchi depths derived from August –September 2000.

Wind mixing and Water movements

The wind speed over the lake is gentle to moderate, with maximum wind speeds during storms rarely exceeding 12 m/s. The waves generated by the wind are correspondingly low, with maximum (1 in 100 years) significant wave heights of 2.5 m. The daily waves generated by the onshore-offshore breezes normally do not exceed 1 m. The waves cause mixing of the surface waters of Lake Victoria to depths of 5-15 m.

Langmuir circulations are generated by surface waves at wind velocities above 2 to 3 m/s. Streaks are seldom observed at wind speeds above 7 m/s, even though the Langmuir circulations are still occurring, for at high wind speeds, surface turbulence is apparently great enough to disrupt the surface aggregation. These currents are sufficient to markedly influence the distribution of micro flora and fauna suspended in the surface waters of lakes. Algae and zooplankton, with limited or no powers of locomotion, tend to be aggregated in streaks in areas of water divergence. The result is the non-uniformity in the distribution of biodiversity that is important not only in sampling of organisms for estimation of population size and distribution, and in metabolic measurements, but also in determining the distribution of predators, which converge in these zones of high prey density (Yamazaki *et al.* 2002).

Average wind directions were plotted for two stations on Lolui and Kome Islands and a station on the northern shores of Lake Victoria. Monthly wind directions are presented in Figure 10. The origins of the wind forces at Masaka are quite different from those that drive the winds at the other two stations on the islands. The two islands experience easterly to south-easterly winds throughout the year. On the contrary, the Masaka station experiences westerly to north-westerly winds most times of the year except in September and October. This implies that while the biggest part of the lake (south of the Sesse Islands) experiences wind patterns that are similar to the global wind patterns, the north-western part of the lake (north of Sesse islands) might be influenced by different wind patterns.

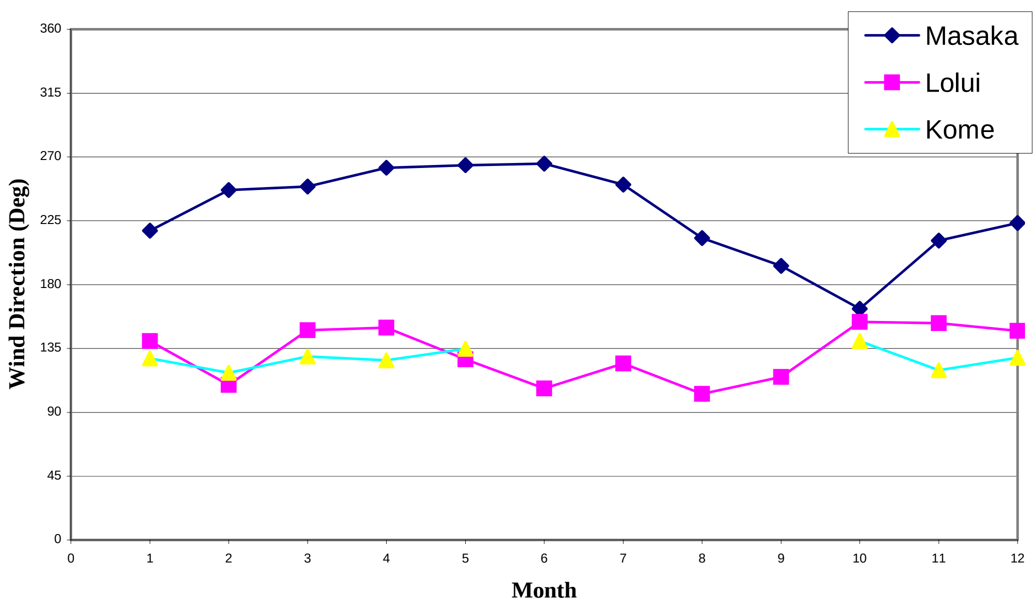

FIG. 10. Monthly average wind directions for Kome, Lolui, and Masaka stations.

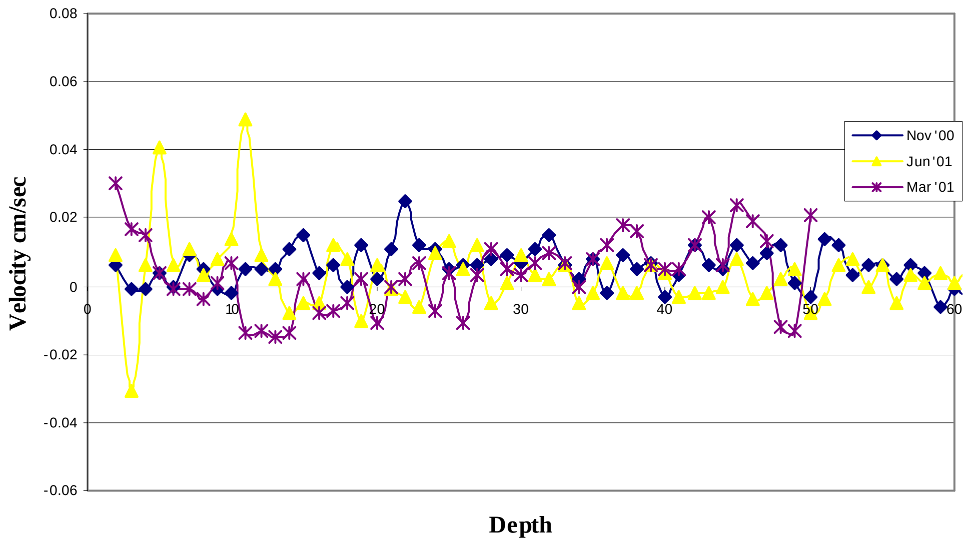

FIG. 11. Vertical velocities for UP8 at selected times of the year.

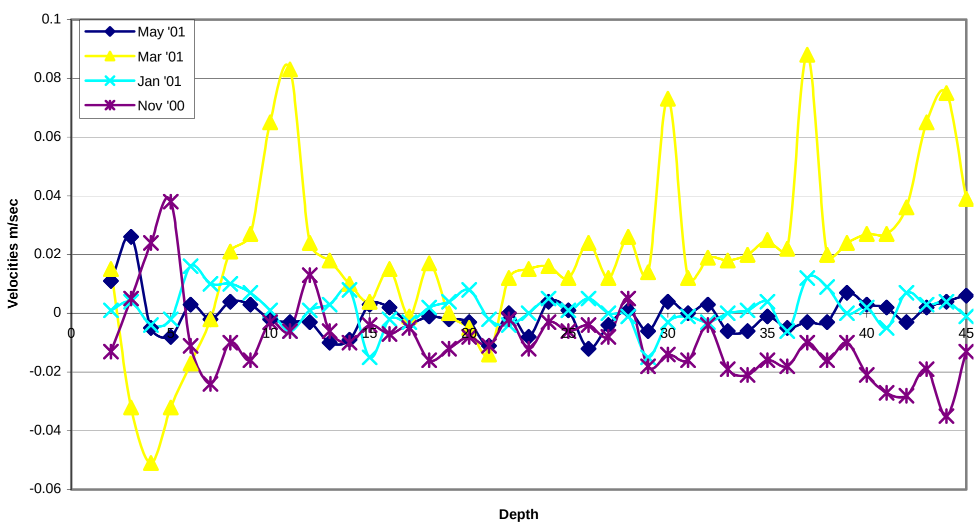

FIG. 12. Vertical velocities for UP6 at selected times of the year.

The upward and down motions are brought about by the cycloid motion caused by the surface waves that have quite a big influence in about the top 10 m and diminishes thereafter.

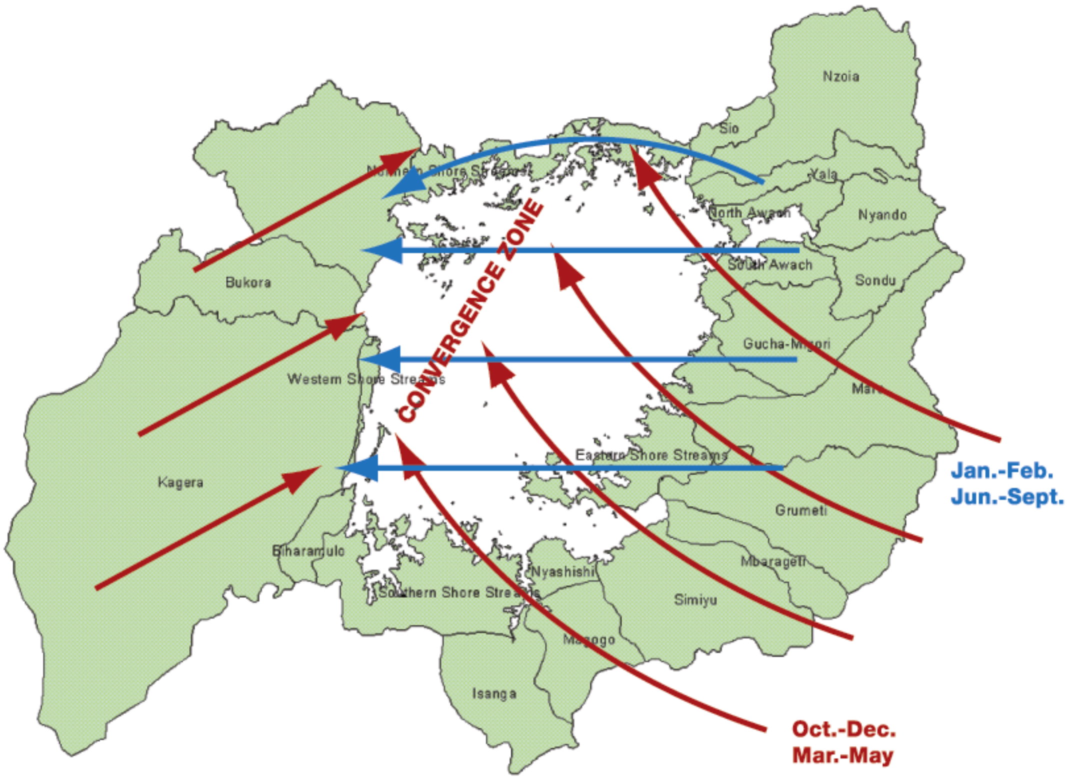

FIG. 13. Global wind patterns over Lake Victoria.

The global wind pattern (Figure 13) shows that from October to December the winds approach the lake from southeast and, as they cross the lake, they turn towards north. At the same time there is a wind stream from Congo approaching the lake from southwest. These two wind streams meet in a convergence zone along the western side of the lake creating very strong surface waves on the western part of the lake. From February to May the main global winds flow from east to west. By the time these winds reach the western part of the lake, they have a long fetch (uninterrupted movement by land). Therefore these winds are capable of creating very high waves on the western part of the lake. As deep-water surface waves enter shallower waters on the western part, their velocity decrease proportional to the square root of depth. A reduction in wavelength occurs with a marked increase in wave height.

With increased height the waves become asymmetrical and unstable and hence very turbulent. For example, a maximum wave height of 1.2 m was recorded at UL9 (a station on the western side of the lake) with wind velocities of only 4.5 m/sec while a 0.5 m wave height was recorded at UP10 from winds of maximum speed 4.7 m/sec. This accounts for the mixing of the water column on the western part of the lake for most period of the year. These strong movements cause very turbulent water mixing that reach the bottom of the lake and thus possible re-suspension of bed material as may be seen in Figure 14 March upward velocity currents. The turbulent mixing coupled with cold rains in this period of the year results in cooler water profiles in this part of the lake. The strong currents force the suspended solids in rich waters of River Kagera to move along the northern shores of the lake to join with the inflows from River Bukora, both of which continue eastward and slowly mix with the northern shore waters. From west to east, these forces decrease and capacity to have a fully mixed layer decreases.

Between January to February, and June to September the eastern part of the lake is shielded from the easterly winds by the Kenyan islands and their influence on heat distribution is felt only within the top 10-15m. Secondly, development of very strong and high waves is largely hampered by short wind fetch coupled with deep waters. Wind movements in this area are largely due to land and sea breeze phenomena. However, due to increased solar radiation between January and February, wind movements are much stronger and therefore surface currents are more pronounced. Mixing is largely due to the cycloid movements due to surface waves and Langmuir circulations. Mixing of the waters in this part of the lake is very minimal and heat transfer is largely due to advection due to the heating and cooling of the surface waters. Much as there are markedly very small temperature gradients in the whole water column, there is relative stability in the water column during this time of the year due to the influence of weak winds.

Between March to May, and October to December, the eastern part of the lake experiences some increased wave action from the southeast winds and remarkable increase in the wind fetch. However, due to the deep-water column, development of turbulent waves is minimal and therefore minimal impact. The result of these actions is a cooler and mixed western part of the lake, and warm and hardly mixed eastern part of the lake.

The areas north of the Sesse islands are shielded from the south-easterly winds by the islands and they are greatly influenced by the Congo westerly winds in the period between October-December and March-May. This creates a situation of strong westerly wind flow above north of the island and therefore surface waves move towards the east. This can be confirmed by observing the movement of the turbid River Kagera water and movement of the water hyacinths from the same river towards Dimo and Bukakata during these periods of the year. This results in the distribution of sediments and nutrients from River Kagera to the northern shores of Lake Victoria around Dimo and Bukora.

On the contrary, between January to February, and June to September, the easterly winds act independently, forcing River Kagera waters to the west. This coupled with the wave strength as described above, the River Kagera waters are forced to mix with the main lake waters and pieces of squashed water hyacinth can be seen scattered all over the western shoreline in incidences where the Kagera River carries it.

Oxygen Distribution

Figure 14 shows the minimum depth at which oxygen concentration of 4 mg/l has been observed within the sampling period between 1994 and 2004. When Oxygen levels get below 4 mg/l, fish and mobile animals migrate to areas of higher oxygen concentrations. From the map, it is evident that the western part of the lake below River Kagera has the most favourable oxygen conditions for fish and other animals throughout the year. The northern shores of Lake Victoria are badly hit especially areas near the influence of Rivers Katonga, Bukora and Sio; and the Gulfs of Napoleon and Wanyange (Semalulu *et al.* 2003).

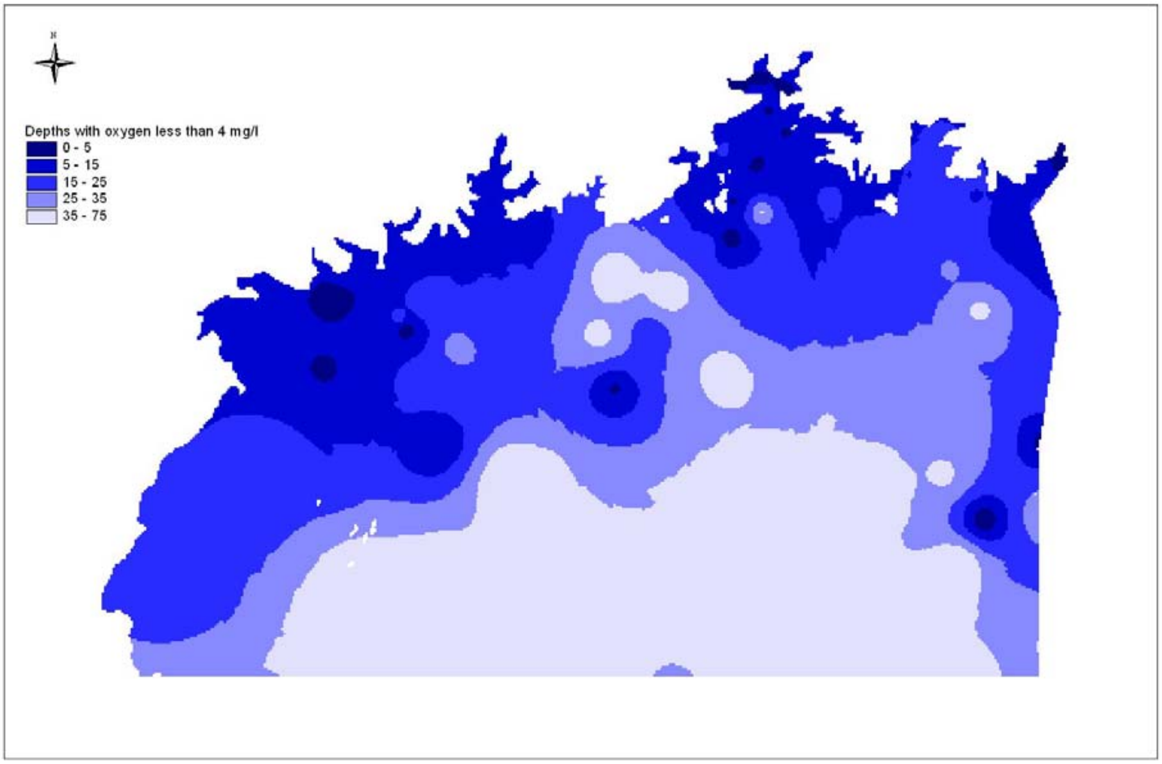

FIG. 14. Oxygen distribution of less than 4 mg/l, 1994-2004.

Seiches

Seiching is a resonance phenomenon like the oscillation of water back-and-forth in a bath tub (Rueda and Schladow 2002). It can occur on Lake Victoria during strong wind events that cover most of the lake. A half-wave oscillation mode across the lake would have a period of 5-6 hours.

Internal Seiches: Internal seiching is a phenomenon where the thermocline or interface oscillates in the same way as the surface, causing intense vertical mixing and upwelling at the shores. If a thermocline developed over most of the lake area, it is possible that internal seiching could occur in Lake Victoria.

Examinations of currents at different depths at UP8 show consistent flow in particular directions that tend to reverse after about 5-14 days in the surface currents for the first 20m. The flow is counterbalanced by a reversal flow at lower depths. However, the reverse flow is much weaker than the surface currents. The decrease in flow strength may be a result of moving a comparatively bigger water mass. A typical example is shown in Figure 15. This may suggest existence of seiching but this phenomenon needs further research.

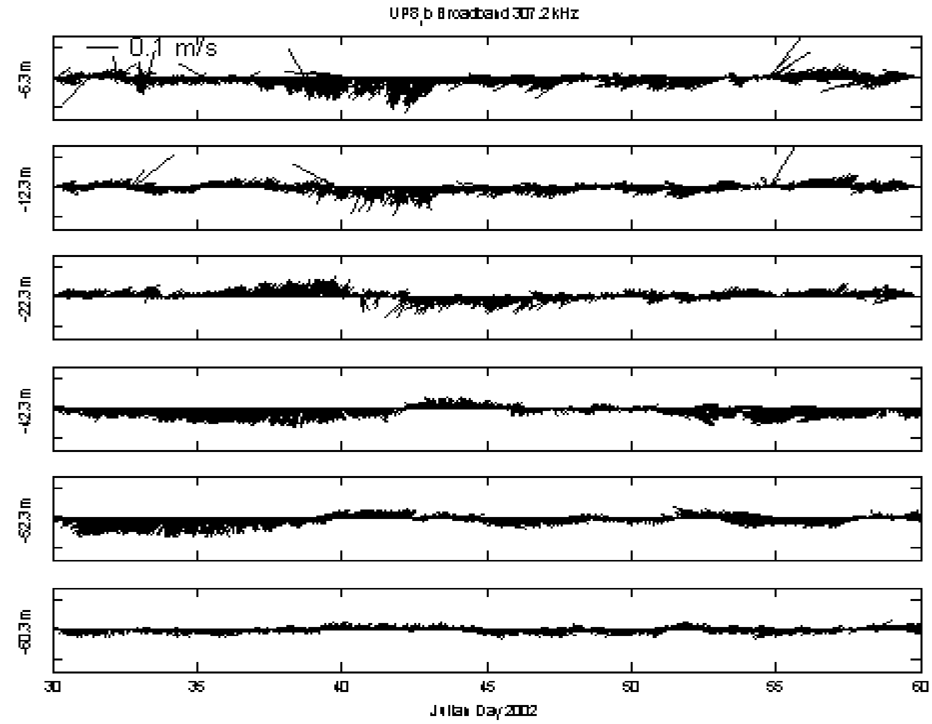

FIG. 15. Velocities at UP8 measured from January to April 2002.

River Inflows

Water entering Lake Victoria from several rivers may have different temperatures from that of the lake. If the river water is warmer, hence less dense, it spreads out over the top of the lake water. If it is colder, it sinks to the bed and spread out under the lake water. If the lake is stratified, the river water may sink to the level of the interface and spread out. Under all circumstances, these phenomena will be restricted to the immediate vicinity of the river mouth (a few kilometres from the river influence). For River Kagera, it might be felt up to 5 km from the mouth. It may not be important for the overall circulation patterns in the lake but it affects the northern shores of the lake.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Examination of the temperature profiles, wind patterns, secchi depths and oxygen profiles lead to the following conclusions:

1. Phases 2 and 3 of the annual cycle as defined by Talling (1966) have been confirmed on the eastern part of the lake. Phase 2 is the development of the deep (40 m) thermocline in the period February to May, and phase 3 is the total vertical mixing that occurs in July-August. Phase 1 (September-December) is less obvious, i.e. the gradual warming of the water column is weak, and almost total mixing occurs in December-January at some stations.
2. The western part of Lake Victoria is much influenced by the wind forces and therefore experiences more mixing and cooling patterns. The eastern part of the Lake is much more influenced by thermal

stratification patterns and therefore mixing is mainly by density currents. This implies that there is more potential for nutrient transfer in the western part of the lake, which may imply favourable conditions for fish cage culture. On the contrary, it also implies that nutrients from River Kagera and the western shores are capable of moving into the deeper waters of the lake.

3. Due to a lower rate of light penetration in the eastern part of the lake, and weaker mixing action, the eastern part of the lake experiences higher water temperatures throughout the year. This may imply higher capacity for primary production in the eastern part of the lake.
4. The northern shores of Lake Victoria experience critical oxygen levels especially near Rivers Sio, Bukora and Katonga influents and also around Entebbe.
5. River Katonga plays a very big role in the nutrient loading and therefore management of a significant part of the north-western inshore areas of the Ugandan portion of Lake Victoria.

Recommendations

Observations of temperatures and currents should be done continuously to understand the forces that drive the generation and govern the delay of the variable flow for the various embayments and the almost closed bays with the central lake.

More emphasis should be made towards the implementation of the hydrodynamics model available so that management issues can be investigated and potential solutions discussed.

A detailed bathymetric survey is required for the project to develop proper model development and calibrations and investigation of lake residence time.

Development of a land use management plan for the Kagera basin should be taken as a priority as its impacts on the northern lake shores is very significant.

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