Morphometry and Physical Processes of East African Soda Lakes

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Abstract

The altitudes of the saline lakes in the East African Rift System (EARS) vary from below sea level in the Danakil Depression (−155 m) to 2000 m in the Ethiopian highlands; most lakes are located above 1000 m. These lakes are among the largest (Turkana) and deepest (Shala) saline lakes in the world, though many formed by volcanism or lahars are small. High concentrations of phytoplankton or suspended sediments lead to high light attenuation, with Secchi visibilities usually less than 1 m. In the shallow, saline lake strong stratification usually develops during the day with mixing to the bottom at night. Seasonal variations in stratification and mixing have been observed in the deep lakes. Topography alters winds and mixing in lakes within volcanic craters. Chemically stratified, saline lakes occur throughout the EARS, and meromixis was documented in Lake Sonachi. Seasonal variations in thermal stratification and horizontal and vertical gradients in salinity occur in Lake Turkana. Only brief visits, occasional year-round studies and long lapses in the study of soda lakes of the EARS leave large gaps in our understanding of temporal variations in their limnology and their responses to climatic and human-caused changes in their hydrology.

3.1 Introduction

Physical characteristics of lakes include their location, altitude, area and depth, optical conditions and stratification and mixing. These characteristics reflect geologic and climatic history and influence ecological and chemical features of the lakes. We examine the physical characteristics of East African soda lakes

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(EASL) by summarizing the available literature and offering perspectives based on current understanding of physical processes. Data on hydrodynamics of these lakes are scarce and largely based on studies in the 1970s and 1980s.

The semiarid EARS extends from northern Tanzania into the Danakil Depression in Ethiopia and Djibouti. Tectonic and volcanic activities have formed the lake basins (Table 3.1). Small lakes within volcanic craters are scattered throughout and include the Basotu lakes (Tanzania; Downie and Wilkinson 1962) and Bishoftu lakes (Ethiopia; Prosser et al. 1968). The Momela Lakes were formed by a lahar that originated on Mt. Meru (Tanzania; Hecky 1971). Both broad, shallow lakes and large, deep lakes occupy tectonic basins.

No rivers flow to the ocean from the EARS; hence, the lakes are within endorheic basins. As a consequence, most of the lakes are saline because solutes are concentrated by evaporation, and the lakes vary considerably in depth, size and salinity as a function of variations in rainfall. These variations occur seasonally, interannually and over longer time periods. Early geological and archaeological expeditions noted relict shorelines above the extant lakes, and subsequent analyses based on radiocarbon dating of sediment cores and use of microfossils to infer salinities and water levels indicated a wetter

Table 3.1 Morphometric characteristics of lakes and mode of origin of basin

Name	Altitude (m asl)	Area (km^2)	Mean depth (m)	Maximum depth (m)	Basin origin
Assal[a,b]	−155	54	7.4	40	Tectonic
Abhe[b]	240	350	8.6	37	Tectonic
Arenguade[c]	1900	0.54	18.5	32	Volcanic crater
Kilotes[c]	2000	0.77	2.6	6.4	Volcanic crater
Biete Mengest[c]	1850	1.03	17.5	38	Volcanic crater
Bishoftu[c]	1870	0.9	55	87	Volcanic crater
Pawlo[c]	1870	0.6	38	65	Volcanic crater
Chitu[b]	1600	0.8		21	Volcanic crater
Shala[b,d]	1558–1567	329–409	88	266	Tectonic
Abiyata[b]	1578	176	7.6	14	Tectonic
Langano[b]	1582	241	17	48	Tectonic
Turkana[e]	427	8860	28	106	Tectonic
Bogoria[f,g]	963	33	5.4	9	Tectonic fault scarp
Nakuru[h]	1759	36–49	0.4–3.6	0.6–4.6	Tectonic
Elmenteita[i]	1776	20	0.7–1.1	0.85–1.35	Tectonic
Sonachi[i]	1891	0.18–0.16	3.8–4.0	6.1–7.0	Volcanic crater
Oloidien[j]	1890	5.5	5.6	8.4	Tectonic
Magadi[a]	660, 683	108			Tectonic
Magad[k]	1722	17		2	Volcanic caldera
Manyara[k]	960	413		3.7	Tectonic fault scarp
Natron[a]	675	1000			Tectonic
Eyasi[a]	1030	1050			Tectonic
Reshitani[k]	1448	0.2		29	Lahar
Big Momela[k]	1448	0.9		31	Lahar
Embagai[l]				75	Volcanic crater
Tulusia[l]				13	Lahar
Lekandiro[l]				11	Lahar
Gidamuniud[l,m]	1600	0.02		9	Volcanic crater

Sources: (a) Serruya and Pollingher (1983), (b) Wood and Talling (1988), (c) Prosser et al. (1968), (d) Melack (1983), (e) Spigel and Coulter (1996), (f) Melack et al. (1981), (g) World Lake Database (1999), (h) Vareschi (1982), (i) Melack (1976), (j) Gaudet and Melack (1981), (k) Melack and Kilham (1974), (l) MacIntyre and Melack (1982), (m) Kilham and Cloke (1990) climate in the early to mid-Holocene (Livingstone 1975; Halfman and Johnson 1988; Street and Grove 1976; Verschuren 1996).

3.2 Morphometry

Morphometric data are available for only a subset of EASL (Table 3.1; see Schagerl and Renaut, Chap. 1). Given the changes in water level caused by variations in rainfall and evaporation, the morphometric data summarized in Table 3.1 represent only depths and sizes when the lakes were studied. The altitudes of the lake surfaces vary from below sea level in the Danakil Depression (−155 m) to 2000 m in the Ethiopian highlands; most lakes are located above 1000 m. Melack (1981) provides a compilation of tropical soda lakes throughout Africa with morphometric divisions as shallow (<2 m), intermediate depths (between 2 and 15 m) and deep (>15 m) and as small (<5 km^2) and large (>5 km^2).

Several EASL are among the largest and deepest saline lakes in the world, although they are not listed as such in Hammer (1986). With the Aral and Caspian Seas excluded, Lake Turkana would be within the top five by area and top ten by depth; Shala (Ethiopia) would be within the top five by maximum and mean depth. In contrast, the volcanic crater lakes and those formed by a lahar are small (0.015–1.03 km^2), though can be fairly deep (up to 87 m, Bishoftu, Ethiopia).

3.3 Optical Conditions

The EASL often have high concentrations of phytoplankton or suspended sediments, leading to high attenuation of incoming light with several limnological and ecological implications. Thermocline depth, vertical nutrient fluxes, rates of photosynthesis and predation rates are all related to penetration of light through the water column. We summarize estimates of underwater transparency made with Secchi discs and attenuation of light measured with underwater sensors. Photosynthetically available radiation (PAR, 400–700 nm) was measured with a filtered, cosine-corrected silicon photodiode (Biggs et al. 1971). Light attenuation was determined in three spectral regions (495, 540 and 650 nm; 50 % bandwidth was 75, 50 and 75 nm, respectively) with filtered photoresistors and ohmmeter (Melack and Kilham 1974) or in four spectral regions (460, 540, 630 and 685 nm) with filtered selenium barrier-layer sensors and microammeter (Talling et al. 1973). The visual colour apparent to a human observer was also noted, and turbidity, expressed as Jackson Turbidity Units (JTUs), was measured with a Hach DR-EL portable instrument. JTUs are an inverse measure of the length of a column of water needed to completely obscure a light source viewed through it, i.e., the lower the value, the clearer the water.

Among the EASL, Secchi disc visibilities varied from 0.1 to 1.0 m with the exception of Lake Turkana (Table 3.2). The abundant phytoplankton common in these lakes is a primary and persistent cause of the shallow Secchi disc visibilities as indicated by Jenkin's (1936) observation at Lake Nakuru in 1929 matching those in the 1970s. P. Kilham (personal communication), as part of his chemical survey of Africa lakes (Kilham 1971), recorded turbidites, as JTUs, in several eastern Rift Valley saline lakes: Big Momela (58), Lekandiro (115), Tulusia (34), Reshitani (40), Small Momela (44) and Embagai (40). All these values are high and indicative of the suspended particles, most likely phytoplankton based on visual observations.

As noted by Talling et al. (1973), in very dense suspensions of phytoplankton, such as those found in Ethiopian lakes Arenguade and Kilotes, it is difficult to obtain high accuracy in measurements of underwater light. Even so, the attenuation coefficients reported for these two lakes are extraordinary (Table 3.2). Other lakes with abundant phytoplankton had attenuation of PAR or visible wavelengths usually 1 and 10 m^{-1}. The very high attenuation in Lake Manyara was caused by suspended sediments. The elevated attenuation values enhance the heating of the water by

Table 3.2 Secchi disc visibility (m), underwater light attenuation (m^{-1}) and visual colour

Lake	Secchi	PAR	460	495	540	630	650	685	Visual colour
Arenguade[a]	–	–	110	–	60	30	–	25	Green
Kilotes[a]	–	–	30–50	–	10–20	8–20	–	7–18	Green
Shala[b]	–	–	3	–	1.3	1	–	1	Clear
Abiyata[b]	–	–	9.5	–	4.6	4.8	–	4	Green
Langano[b]	–	–	8.5	–	6.5	3.1	–	3	Reddish brown
Turkana[c]	1–4.8	–	–	–	–	–	–	–	–
Bogoria[d,e]	0.28–0.60	–	–	–	–	–	–	–	–
Nakuru[f]	0.15	–	–	10	12	–	15	–	Green
Nakuru[g]	–	3.6–17.0	–	–	–	–	–	–	Green
Elmenteita[f]	0.17	–	–	7	9	–	30	–	Green
Elmenteita[d,i]	0.12–1	1.9–3.6	–	–	–	–	–	–	Green to yellow
Elmenteita[e]	0.15	9.2	–	–	–	–	–	–	Green
Sonachi[e,h]	0.3–0.55	1.9–3.5	–	–	2.3–3.8	–	–	–	Yellowish green
Oloidien[j]	0.5–1.0	1.3–2.4	–	–	1.7–2.9	–	–	–	–
Magad[f]	0.1	–	–	4	4	–	4	–	–
Manyara[f]	–	–	–	16	100	–	80	–	–
Reshanti[f]	–	–	–	4	5	–	7	–	Green
Big Momela[f]	0.25	–	–	4	6	–	5	–	Green
Embagai[k]	–	–	–	1.8	2.6	–	2.5	–	–
Gidamuniud[k]	–	–	–	1.2	1.1	–	0.9	–	–

Sources (a) Talling et al. (1973), (b) Wood et al. (1978) (estimated from Fig. 3.2), (c) Källqvist et al. (1988), (d) Melack (1981), (e) Melack et al. (1981), (f) Melack and Kilham (1974), (g) Vareschi (1982), (h) Melack (1982), (i) Melack (1976), (j) Melack (1979), (k) P. Kilham, personal communication

insolation, with concomitant strong stratification during the day.

3.4 Stratification and Mixing

The EASL are generally warm, including those in highlands of Ethiopia. At temperatures near and above 20 °C, warming of the upper waters in the day and cooling at night cause appreciable changes in density and lead to pronounced cycles of diel stratification and mixing. The high evaporation at warm temperatures contributes to surficial cooling and nocturnal convective mixing. Furthermore, since seasonal variations in temperature are slight, temperature gradients between surface and bottom waters are not large. As a result, shallow lakes are usually polymictic with daily or frequent stratification and mixing to the bottom. Seasonal stratification occurs in deep lakes. General reviews of stratification and mixing in tropical lakes are provided in Beadle (1981), Livingstone and Melack (1984), MacIntyre (2012, 2013), Talling and Lemoalle (1998) and Spigel and Coulter (1996), and a more comprehensive discussion is in MacIntyre et al. (2002, 2014).

3.4.1 Shallow Lakes

In shallow, saline lakes, strong stratification usually develops during the day with mixing to the bottom at night (Melack 2009; Melack and Kilham 1974; Vareschi 1982). Time-series observations in Lake Elmenteita, Kenya (Fig. 3.1), obtained over 13 months, indicate a high degree of predictability, based on information theoretic indices, in stratification dynamics (Melack 2009).

As the wind passes across the surface of a stratified lake, the thermocline usually tilts, and velocity shear develops within it. Whether shear-induced instabilities will form in the thermocline and become turbulent can be predicted from the Richardson Number, $Ri = -g \ \rho^{-1} \ (\delta\rho/\delta z)$

Fig. 3.1 Lake Elmenteita with evaporative soda deposits in foreground. Photograph by J. Melack, June 1973

$(\delta u/\delta z)^{-2}$ where g is gravity, ρ is density, u is velocity and z is depth. If *Ri* drops below 0.25, the fluid will become turbulent and mix. In one of the few analyses of *Ri* for a tropical lake, MacIntyre (1981) and MacIntyre and Melack (1995) report vertical profiles of current speeds, measured with a warm-bead thermistor sensor (MacIntyre 1986), and temperature in Lake Nakuru. Temperatures taken through the day document morning stratification followed by afternoon and evening mixing, as expected from previous studies noted above. The stability of the stratification, determined from the Brunt-Väisälä frequency, $N^2 = -g\,\rho^{-1}\,\delta\rho/\delta z$, indicated strong stratification during portions of the day. Temperature fluctuations in the stratified regions suggested high-frequency internal wave motions. Currents, measured on November 29, 1976, at 0.07, 0.11, 0.37 and 0.95 m, were less than 2.5 cm s^{-1} except at 0.11 m. At 0.11 m, they were highest at noon, reaching 5 cm s^{-1}, and decreased throughout the afternoon. Richardson numbers were either negative, implying heat-loss-augmented wind mixing due to winds of 3–5 m s^{-1} during the afternoon, or close to the critical value for turbulent mixing above the thermocline and much larger than the critical value across the thermocline. The high values imply reduced flux between the upper and lower water column during the day. The persistent stratification enabled anoxia to develop in the lower water column during the day, which would then enable phosphorus to be in ionic form and support growth of autotrophs. The reduced mixing also enabled buoyant Cyanobacteria to control their vertical position in the water column.

Intermittent winds can induce surface seiches. Based on the morphometry of Lake Nakuru, Vareschi (1982) calculated a theoretical period of ~1.3 h. Following a windy period, an automatic stage recorder documented a period of 1.1 h and an amplitude of 4.5 cm. While conducting diel measurements at Lake Elmenteita, occasional solitary, surface waves of ~ 10 cm amplitude were observed. We inferred that these waves were surface seiches.

3.4.2 Crater Lakes

Prosser et al. (1968) noted that the variation in the height of the crater rim surrounding a crater lake is likely to influence the extent to which wind reaches the lakes and moderates stratification and mixing of the water. Subsequently, Melack (1978) proposed an index of the exposure to wind-induced mixing as the ratio $D\,H^{-1}$, where D is the maximum diameter of the lake and H is the minimum height of the crater rim above the lake. Wind is an important factor, as the energy imparted to a lake by wind causes currents and shear and internal and surface waves, and contributes to evaporative cooling and convective mixing. The ratio explained 31 % of the variation in the depth of anoxic or hypoxic water measured in a number of African crater lakes. Scatter in the relation is expected given the multiple processes that determine stratification and because mixing depth can vary on timescales from hours to months to years.

Stratification and mixing in the upper waters of tropical crater lakes occur on a diel basis (MacIntyre 1981; Melack 1976, 1982; Talling et al. 1973). Within sheltered Lake Sonachi (Fig. 3.2), diurnal heating occurred in the upper metre with cooling restricted to the upper 3 m in May 1973 (Fig. 3.3). The extent of heating and cooling offshore varied with solar radiation, wind speed and its timing during day and night, light attenuation and lateral transport due inshore and offshore differences in temperature. For example, on November 1 and 2, 1976, daily insolation was 356 and 321 W m^{-2}, respectively. Underwater attenuation of PAR was 3 m^{-1}; hence, the 1 % light level was at 1.5 m. Wind, measured on a mid-lake platform (Fig. 3.4), ranged from 0.5 to 7.5 m s^{-1} with significant diel variations (Fig. 3.5). Crater walls rise 33 to 117 m above the lake (Fig. 3.6), and the lakeshore is fringed by *Acacia xanthophloea* trees. As the lake heated in the morning, thermal stratification developed and peaked in mid-afternoon with temperatures differing by as much as 4 °C in the first metre (Fig. 3.7). After nocturnal cooling, stratification was minimal around dawn. Temperature oscillations in thermally stratified regions ranged in amplitude from 0.05 to 1.60 °C and probably indicate short-period internal waves. By late afternoon, cooler temperatures occurred near the surface than in the water below; these decreases are indicative of surficial cooling leading to convective mixing. Thermal stability, calculated according to Idso (1973), was least in the early morning and increased with increases in the lake's heat content (MacIntyre and Melack

Fig. 3.2 Lake Sonachi in foreground; only the southern portion of the volcanic crater around Lake Sonachi is shown. Aerial photograph by J. Melack, January 1971

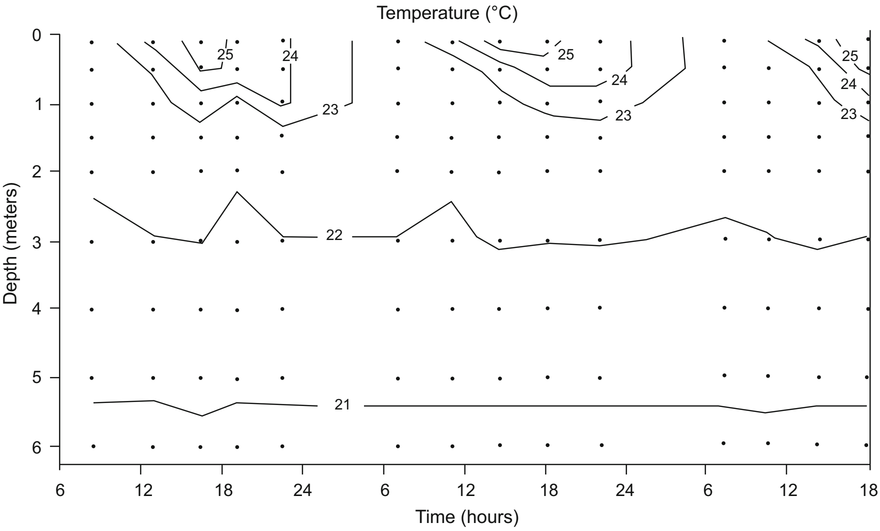


Fig. 3.3 Time-depth diagram of temperature in Lake Sonachi, 5–7 March 1973. From Melack (1976)

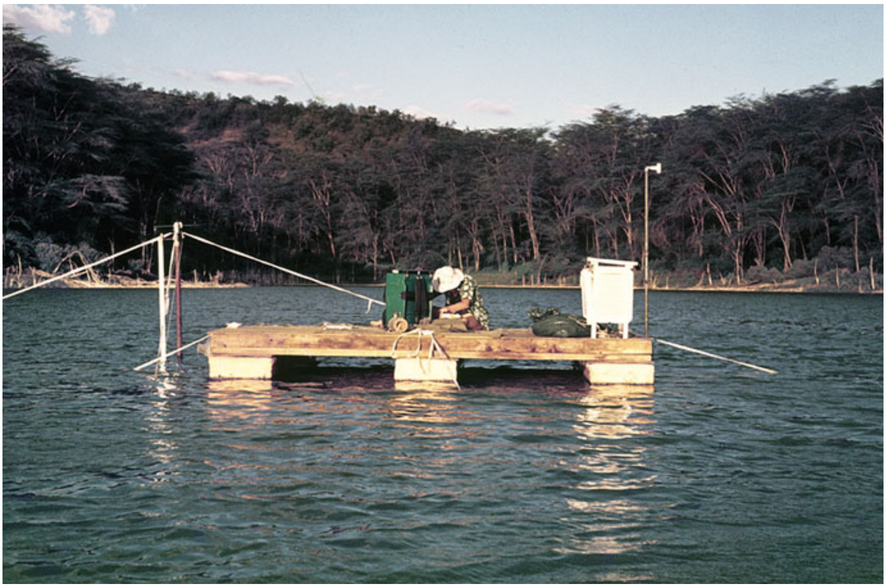


Fig. 3.4 Research platform with mast for current sensors and pole for wind sensor and housing for recorder, Lake Sonachi. Photograph by J. Melack, November 1976

1982). On November 1, mid-afternoon (1420 h), thermal stability was 8.7 J m^{-2} and on November 2 at 1500 h was 10.5 J m^{-2}.

Conditions in Lake Sonachi in the morning and early afternoon indicate that most of the turbulent kinetic energy imparted by the wind was consumed by work against the buoyancy produced by solar heating. In other words, stable stratification and Richardson's numbers between 0.05 and 100 developed during morning and early afternoon despite morning winds reaching 6 m s^{-1}. In fact, the strongly stratified region reached the surface (MacIntyre 1981). Brunt-Väisälä frequencies were high (0.03–0.12 s^{-1})

Fig. 3.5 Wind speeds (m s^{-1}), Lake Sonachi, November 1–2, 1976. Wind speeds were measured mid-lake, 1.9 m above the water with a 3-cup anemometer and chart recorder and averaged for 15-min periods. From MacIntyre (1981)

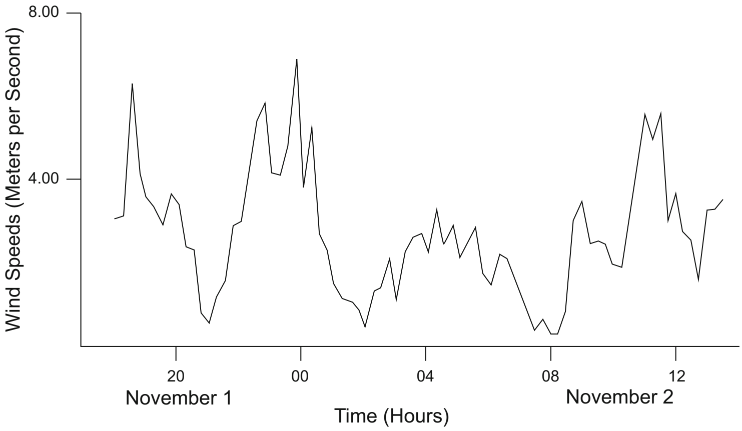
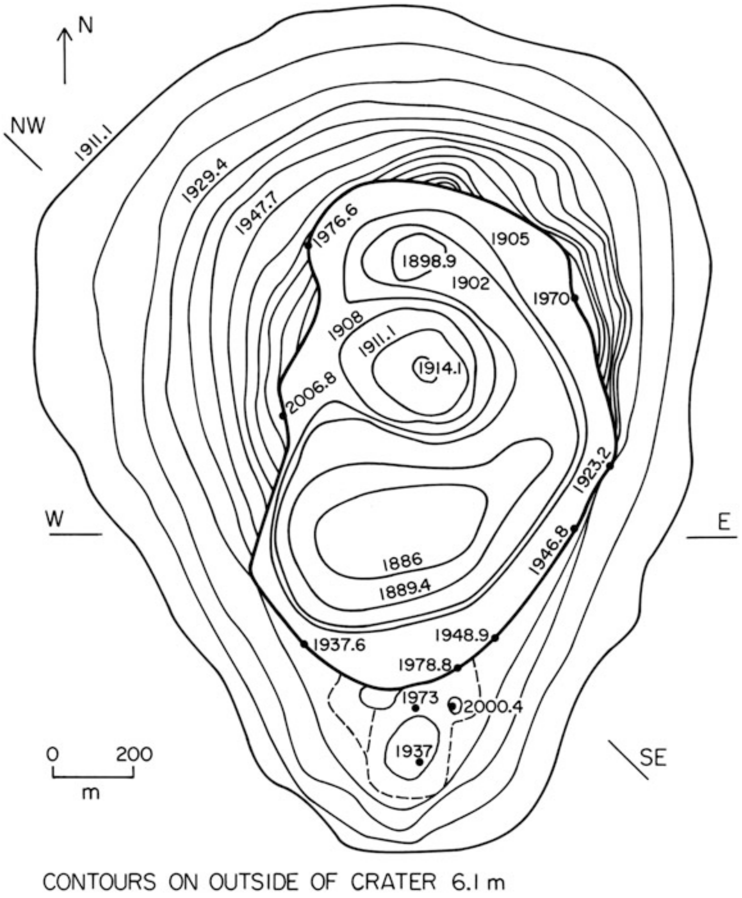


Fig. 3.6 Volcanic crater and surrounding hillside around Lake Sonachi derived from Kenya Ministry of Works drawing #44,330 at 1:1000 scale. Lake lies between 1886 and 1889.4 m contours in lower half of crater. From MacIntyre (1981)



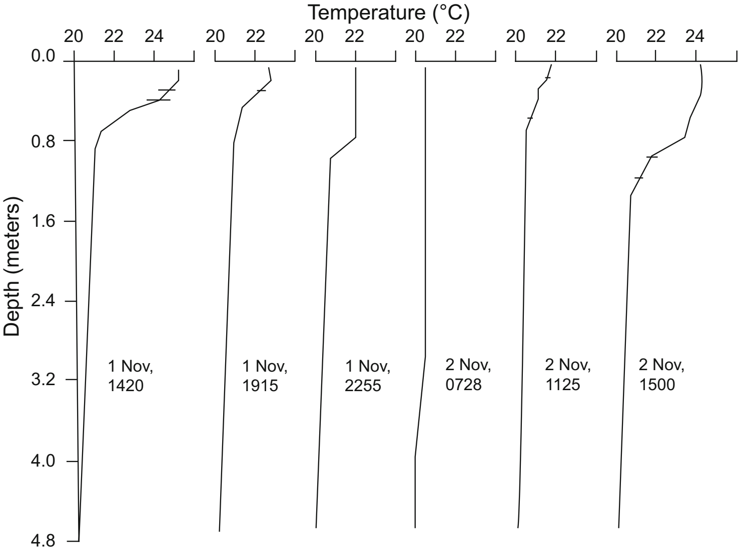


Fig. 3.7 Temperature profiles, Lake Sonachi, 1–2 November 1976. Horizontal bars indicate range of temperature oscillations. Measurements made at 0.1 m intervals in first metre, at 0.2 m intervals in the second metre and at 0.5 m intervals until 4.5 m. From MacIntyre (1981)

near the surface, and temperature oscillations pointing to high-frequency internal waves were present. *Ri* computed for 0.3 m intervals occasionally decreased below the critical value of 0.25. Values below 0.25 indicate that conditions were sometimes conducive to overturning internal waves and intermittent turbulence in the stratified upper region. The temperature inversion between 0.3 and 0.4 m at 1125 h on November 2, 1976, provides an example of a shear instability (Fig. 3.3). Overall, however, the stabilizing effect of heating exceeded that from wind-induced shear, and near-surface mixing did not begin until later in the afternoon when heat loss began to dominate the surface energy budget.

Seasonal variations in stratification and mixing have been observed in some crater lakes. For example, Wood et al. (1976) documented seasonal holomixis in Lake Babogaya (formerly Lake Pawlo), one of the Bishoftu crater lakes. With clear skies in January and February, heat loss by long-wave radiation increased to maximal values. Latent heat fluxes are expected to have increased with the concomitant decrease in relative humidity, and sensible heat fluxes are expected to have increased as air temperatures dropped. Thus, nocturnal cooling would have been increased relative to that during other seasons and led to the destratification and mixing of this lake.

MacIntyre (1981) analysed how crater topography moderates the wind field impacting lakes within volcanic craters and used Lake Sonachi as an example; we summarize this study and relevant theory here. Airflow is affected by atmospheric stratification within and above the crater and by the trees that fringe the lake. Possible patterns of airflow can surmised based on studies of airflows in valleys or behind hills. Bell and Thompson (1980) used experimental data and theory to show that when the Froude number (F) was below 1.3, air in a valley was stagnant. $F = U/Nh$, where U is the wind speed upstream of a hill, N is the Brunt-Väisälä frequency and h is the height of a hill or depth of a valley. F is the ratio of forces that generate mixing to buoyancy forces that resist mixing. Stratification of air within a crater is also influenced by the diel temperature variations of the land within the crater, by the lake and by the relative proportion of the crater occupied by the lake or land. Lake Sonachi occupies only about 20 % of the area within the crater. During the day, heat from the warming land leads to unstable stratification of the atmosphere over the land, while at night the cool ground leads to stable stratification. Lakes tend to be cooler than the air during mid-day, and thus the air is stably stratified and warmer than overlying air at night and the atmosphere unstably stratified. Thus, the proportion of land to water within the crater will determine whether the atmosphere is unstable or stable; this is a first-order control as to when winds penetrate into the crater.

Airflows over a crater lake for stratified or neutral atmospheric conditions inferred from laboratory studies (Hunt et al. 1978; Hunt and Snyder 1980) are illustrated in Fig. 3.7. These conditions would apply during the day when the surface area of the lake is large enough relative to the overall surface area of the crater such that its temperature dominates atmospheric stability. Small boundary layer separations directly behind the crater rim or the trees fringing the lake are not depicted. At $F = 0.2$ (Fig. 3.8a), air within the crater is stagnant, a small hydraulic jump forms near the crater rim, and the boundary layer separation in the lee of the crater extends approximately 100 m over the lake. At $F = 0.4$ (Fig. 3.8b), air within the crater remains stagnant, and the vertical eddies in the wake of the hydraulic jump probably do not reach the lake. At $F = 0.6$, eddies are likely to reach the lake's surface. For F greater than 0.4, lee waves of about the same height as the hill over which the air is flowing may form; unstable regions called rotors can occur in association with lee waves. Bell and Thompson (1980) observed rotors at Froude numbers between 0.8 and 1.2. Above the critical Froude number of 1.3, flow passes though the crater and lee waves form with a rotor (Fig. 3.8c). As wind speed increases and F exceeds 1.7, air sweeps through the crater except for a small region of backflow (Fig. 3.8d). Measured wind speeds often fluctuate rapidly, probably due to interactions with trees and irregular terrain. For example, horizontal fluctuations

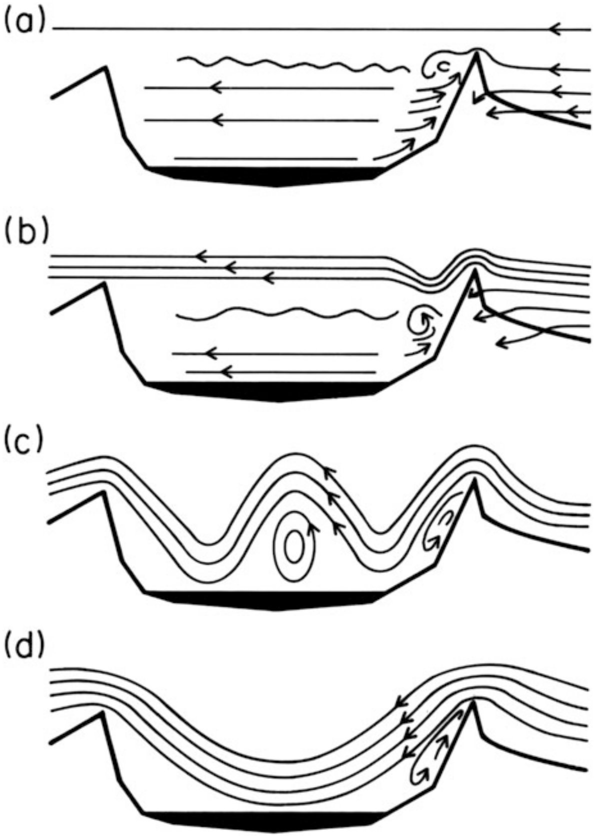


Fig. 3.8 Sketches of air flow over Lake Sonachi at different Froude numbers. Explanation in text. From MacIntyre (1981)

in wind speed were found to be five times greater over a wooded ridge than over smooth terrain (Panofsky et al. 1978).

During the periods when wind speeds outside the crater relative to stratification are too low for them to penetrate, the temperature differences over the lake and over the land within the crater will likely generate lake-land breezes. For Lake Sonachi, the larger land mass suggests that the atmosphere as a whole was unstable during the day and outside winds could penetrate. At night, however, the atmosphere within and outside the crater was likely stable. Hence, when outside winds were light, the greater cooling of the air over the land inside the crater likely generated airflows over the lake. This mechanism would enable heat loss by evaporation at night and contribute to nocturnal mixing. Even in craters in which the lake's surface area is proportionately larger, the greater cooling of the crater walls at night could induce downslope flows and promote heat loss and mixing within the lake.

Given the wide range of crater and lake dimensions among the crater lakes in eastern Africa, winds will impart a wide range of energies to mixing processes. Among the Basotu lakes, the longest dimension of the lakes (L_m) varies from 68 to 700 m; the maximum height of the crater above the lake (H_m) ranges from 12 to 96 m (Kilham and Cloke 1990). The ratio of these two terms (H_m/L_m) ranges from 0.017 to 0.50. Among the Bishoftu lakes, L_m varies from 900 to 1600, H_m from about 40 to about 200 m and the ratio from 0.04 to 0.22 (Prosser et al. 1968). For Lake Sonachi, $L_m = 650$ m, $H_m = 117$ m, and the ratio $= 0.18$. Among the 16 volcanic crater lakes associated with the western Rift Valley in Uganda and examined by Melack (1978), L_m ranged from 75 to 3750 m, H_m from 5 to 215 m and the ratio from 0.0013 to 0.6. The analysis of controls on airflows over crater lakes indicates why the predictive ability is low with the ratio D:H. Further improvement would likely be achieved by including the ratio of lake surface area to crater area and the ratio of daytime to night-time air temperatures. This is because a larger range implies a greater probability of formation of gravity currents, which would cause a land breeze over the lake at night.

3.4.3 Chemically Stratified Lakes

Chemically stratified, saline lakes occur throughout the EARS (MacIntyre and Melack 1982). One consequence of chemical stratification is meromixis, i.e., incomplete vertical mixing over at least several years. The water in the upper portion is called the mixolimnion, while that below the chemocline is called the monimolimnion. To demonstrate meromixis requires repeated measurements over many years, and one of the few lakes in eastern Africa with such data is Lake Sonachi (Kenya). MacIntyre and Melack (1982) described an 8-year period that included a weakening and strengthening of chemical stratification, without complete vertical mixing, as the amount of rainfall varied. Based on an analysis of sediment cores from Lake Sonachi, Verschuren (1999) and Verschuren et al. (1999) inferred meromictic and holomictic periods spanning a few years to several decades over the prior 175 years.

Several aspects of MacIntyre and Melack (1982) are generally relevant to studies of saline lakes. Water density and its changes with temperature are critical when examining stratification and meromixis. Because the solutes dissolved in the waters of soda lakes differ from seawater and are in much higher concentration than in freshwaters, density must be calculated based on physical chemical principles or measured (Boehrer et al. 2010; Jellison and Melack 1993; MacIntyre and Melack 1982; Millero et al. 1976). Because it is usual to measure profiles of electrical conductivity, relationships between the densities and conductivities are needed. Calculating the stability of the stratification, as determined following Idso (1973), and its partition into chemical and thermal components are useful metrics to evaluate the likely persistence of meromixis. In the case of Lake Sonachi, the chemical stability varied from a high of 200 J m^{-2} to a low of

0.7 J m^{-2}, when the lake almost mixed. During the period with lowest chemical stability in 1976, maximum daily thermal stability ranged from 1.95 to 10.5 J m^{-2}.

A rare type of thermal stratification with the warmest water at mid-depth (heliothermy) can occur in small, chemically stratified lakes, and this was observed in Lake Mahega, a crater lake in the Rift Valley of Uganda (Kilham and Melack 1972; Melack and Kilham 1972). The lake had strong chemical stratification, a dense accumulation of pigmented phytoplankton and Bacteria at 1 m and a Secchi disc transparency of 0.33 m, which allowed solar energy to reach the turbid layer. As a result, the water temperature increased from 31 °C at 0.1 m to 40 °C at 1 m and decreased to 37 °C at 3.5 m. Though this type of stratification has not been observed in EASL, the Basotu crater lakes are likely candidates.

3.4.4 Large, Deep Lakes

Lake Turkana, the largest lake in the EARS, is 256 km long with a mean width of 35 km (Spigel and Coulter 1996). It receives almost all its inflow from the Omo River draining from Ethiopia. Its local climate is arid—with precipitation on the lake of 360 mm y^{-1} and evaporation from the lake of 2340 mm y^{-1}—and hot with mean annual air temperatures of 30 °C (Spigel and Coulter 1996). The lake has a salinity of about 2.5‰ (Yuretich and Cerling 1983), with horizontal and vertical gradients in salinity attributed to inputs of less saline Omo River water (Ferguson and Harbott 1982). The larger central basin has a maximum depth of 73 m, while the smaller southern basin has a maximum depth of 106 m. A closed-basin lake with no surface outlet, its water level varies, e.g., levels declined approximately 5 m from 1972 to 1988 (Källqvist et al. 1988). During the southwest monsoon, which typically occurs from May or June through August or September, strong southerly winds can exceed 15 m s^{-1} with persistent winds from 5 to 11 m s^{-1}; these are superimposed on a diel pattern of strong winds in the afternoon and night (Ferguson and Harbott 1982).

Seasonal changes in near-surface waters are about 2 °C, and near-bottom temperatures range from 25.5 to 26.4 °C (Ferguson and Harbott 1982). Time series of vertical profiles of temperature and dissolved oxygen reported by Källqvist et al. (1988) for 1987–1988 indicate prolonged periods of stratification. Temperature and conductivity profiles shown by Spigel and Coulter (1996) for the monsoon-influenced period in 1987 and 1988 vary with depth but lack well-defined mixed layers and thermoclines. A transect of temperature profiles during August and October indicated holomixis in the southern lake and stratification in the north (Ferguson and Harbott 1982). While this pattern perhaps reflects upwelling induced by the strong southerly winds, freshwater inputs from the Omo River are largest from June through September and enter the northern lake as a sediment-laden overflow; this likely enhances stratification. An additional factor increasing the likelihood of a stratified northern versus southern lake is the large difference in the depth of the 1 % light level: 0.5–3.7 m 25 km from the Omo River mouth versus 10.2–13 m 230 km to the south (Ferguson and Harbott 1982; Spigel and Coulter 1996). Based a survey of 11 stations in the northern basin in January 1990, Halfman (1996) reported water temperatures slightly below 27 °C at 40 m and near-surface heating under calm conditions to just over 28 °C.

Lake Shala is a large, deep soda lake within a graben in the Ethiopian Rift Valley. Lake levels were low during the last glacial maximum and high 8000–9000 years B.P. (Beadle 1981; Street and Grove 1976). As summarized by Melack (1983), no chemical stratification was noted by Loffredo and Maldura (1941) or Baxter et al. (1965), but chemical stratification was observed when sampled by Baumann et al. (1975). Both Vatova (1940) and Baxter et al. (1965) reported thermal stratification with near-surface temperatures from 23 to 26 °C and near-bottom temperatures of about 21 °C.

3.5 Temperature Trends and Climate Changes

Though long-term records of water temperatures in EASL are not available, observations of skin temperatures have been reported for three lakes in the region (Schneider and Hook 2010). Following the terminology of Donlon et al. (2002), the skin temperature is that measured by a radiometer within a thin layer (~500 μm) on the water side of the air-water interface. Schneider and Hook (2010) used thermal infrared imagery obtained by the satellite-borne Along Track Scanning Radiometer and Advanced Very High Resolution Radiator series of sensors to examine trends in skin temperature from 1985 to 2009. Night-time values were averaged for the months of January, February and March to capture the warming periods in equatorial Africa. Temperature trends expressed as °C y^{-1} of 0.02 (L. Turkana), 0.05 (L. Eyasi) and 0.02 (L. Abaya) were found. Except for L. Eyasi, which often has shallow water distributed over a salt pan, these rates are less than the global average rate of 0.045 ± 0.011 °C y^{-1}. The lower values may result from the increased evaporative heat losses that accompany heating in warm tropical lakes.

3.6 Future Directions

Only brief visits, occasional year-round studies and long lapses in the study of EASL leave large gaps in our understanding of temporal variations in their limnology and their responses to climatic and human-caused changes in their hydrology. Though recent studies or analyses of ecological aspects are available (e.g., Burian et al. 2014; Krienitz and Kotut 2010; Schagerl and Oduor 2008, see Schagerl and Burian, Chap. 12), few investigations have focused on physical limnology since the early efforts by MacIntyre described above. With the availability of automatic recording systems, robust sensors, remote sensing techniques and models, it should be possible to initiate or continue studies in these lakes. As an example, Tebbs et al. (2013) developed an algorithm to monitor chlorophyll levels in Lake Bogoria and lakes with similar phytoplankton using an orbiting sensor (Landsat). Examples of approaches appropriate to eastern African saline lakes include the applications in a large, saline lake of microstructure profilers to calculate turbulence (MacIntyre et al. 1999, 2009; MacIntyre and Melack 2009), multi-station, time series of temperature and conductivity to document changing density gradients and vertical mixing (Jellison and Melack 1993) and three-dimensional modelling supported by meteorological data and temperature loggers (Vidal et al. 2013). These activities are of increasing urgency as pollutants from urban and agricultural activities and water diversion schemes, compounded by climate changes, are altering inflows to eastern African saline lakes (Dagnachew Legesse et al. 2004; Hadgembes 2006; Melack 1996; Odada et al. 2004; Velpuri and Senay 2012). International partnerships with researchers at universities in Ethiopia, Kenya and Tanzania should be nurtured and collaborative activities and local infrastructure and capacity developed further.

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