

An outline of the physical limnology of Lake Malawi (Lake Nyasa)

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Abstract

Lake Malawi, in tropical central Africa, is 560 by 75 km and consists of a single basin, maximum depth 695 m. Below 250 m the lake is homothermal at about 22.5°C and is anoxic. Above this level there is a seasonal cycle with the development of a marked thermocline. By May the upper 60 m is homothermal at about 27°C. During the dry, windy cool season the epilimnion cools but only in exceptional years approaches a homothermal condition. Complete mixing has never been observed. In the shallower southeast arm the surface temperature may fall to 21.0°C as the result of inshore chilling; this cool water flows northward as a profile-bound density current and appears to maintain the stability of the stratification. Large-scale oscillations of the level of the thermocline, apparently the result of internal waves and of wind-induced upwelling, cause advections of water from the metalimnion into the southeast arm, site of the major fishery in the lake.

Lake Malawi, formerly Lake Nyasa, is the most southerly and the least well documented of the three largest great lakes of Africa.

The earliest limnological information from Lake Malawi was that of Fuelleborn (1900) who observed the first example of a thermocline in a tropical lake. Beauchamp (1953) made detailed observations in 1939–1940. The water below 250 m was anoxic except in one instance on the eastern shore in April near the mouth of a large river, where the oxygen concentration of 0.5 ppm may have been brought about by a density current. He believed the lake was permanently stratified, although, on the strength of low temperatures observed at the extreme south in 1946, he did suggest that it might occasionally mix. In 1954 the Joint Fisheries Research Organization of Northern Rhodesia and Nyasaland began observations on the lake (Jackson et al. 1963) and these were continued by others (Iles 1960; Eccles 1962*a, b*, 1965) who also drew attention to the importance of internal waves. This work presents new results and attempts to correlate them with earlier work and to derive an outline of the physical processes in the lake as a whole.

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Physiography and climate

Lake Malawi is the most southerly of the Great African Rift Valley lakes. It is about 560 km long and has a greatest width of about 75 km (Fig. 1). In contrast with Lake Tanganyika, it consists of a single basin with greatest depth of about 695 m near the western shore north of Nkhata Bay (Fed. Dep. Surveys undated). It lies between 9°30' and 14°30'S at an altitude of about 500 m in a tropical climate. However it lies far enough south of the equator to experience marked seasonal variations in wind, temperature, and precipitation. Table 1 shows mean temperature and dew point for January and July at a number of lakeshore stations. No overall effect of precise latitude is apparent, the ends of the lake experiencing a wider range of temperature than the stations nearer the middle where the lake exerts a moderating effect on climate. Daily maximum and minimum temperatures over a period of 17 months at Monkey Bay are shown in Fig. 2. This period included the coldest weather recorded for about 30 years in southern Africa. The screen minimum at Monkey Bay was 12.2°C on 17 June 1968

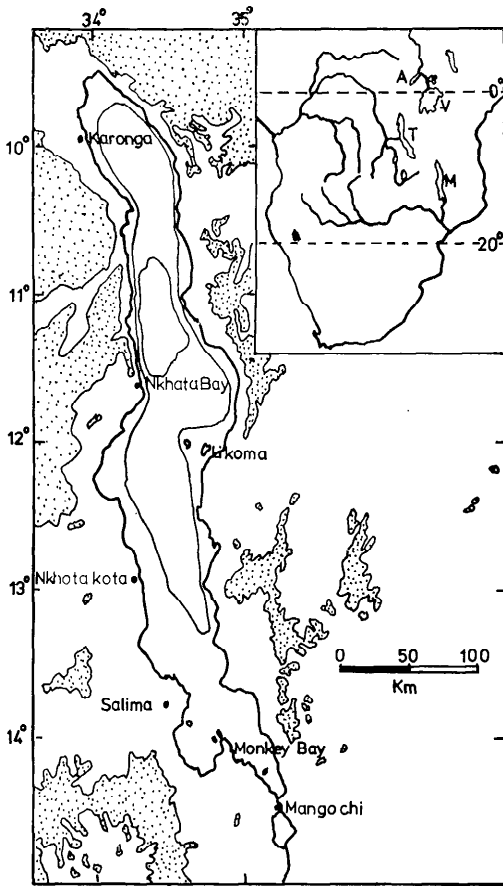


Fig. 1. Map of Lake Malawi showing bathymetric contours for 250 and 500 m, and contour of land over 1,220 m above sea level. The lake level is about 475 m above sea level. Inset shows positions of lakes Albert (A), Victoria (V), Tanganyika (T), and Malawi (M).

when a ground temperature of 4.2°C was recorded at Mangochi and frost occurred on higher ground.

The prevailing winds for much of the year tend to blow along the axis of the lake, to some extent channeled by topography. During the rainy season (November to March) the winds tend to be northerly but between April and May the intertropical convergence zone moves northward and southerly winds become predominant. These winds blow with considerable force for periods of several days, often attaining 40 km hr^{-1} and generating surface waves

Table 1. Climatic data ($^{\circ}\text{C}$) from stations on shore of Lake Malawi (D.P. = dew point).

	Jan means			Jul means		
	Max	Min	D.P.	Max	Min	D.P.
Karonga	29.7	21.8	21.5	26.9	15.0	15.5
Nkhata Bay	28.6	21.3	21.0	25.3	14.3	14.0
Likoma	28.9	22.9	21.0	26.0	19.0	13.0
Nkhotakota	28.2	21.3	21.5	25.4	25.0	13.5
Salima	29.3	21.5	21.5	26.2	15.0	13.5
Monkey Bay	28.9	21.9	21.0	26.5	14.4	13.5
Mangochi	30.2	21.3	21.0	26.5	13.6	14.0

3–4 m high. By September winds are more easterly and may be very strong in the mornings. The lake however exerts a considerable moderating effect on the winds in its vicinity, generating land and sea breezes, the former being particularly strong in the vicinity of high ground. The lower minimum temperatures recorded from Nkhata Bay and Mangochi than from other lakeshore stations are the result of the proximity of high ground.

Annual rainfall over the lake varies from about 65 cm just north of Mangochi, which lies in the rain shadow of the high land to the east and southeast, to 200 cm at Nkhata Bay, and 250 cm near the northern extremity.

With runoff from the land the total annual addition of water to the lake is equivalent to a rise of the surface varying between 1.73 and 2.5 m; the annual rate of loss is more constant, evaporation accounting for about 1.9 m while flow down the Shire River at the present high lake level takes only about 45 cm (Pike 1964). Water gains and losses occur simultaneously at differing rates so that the annual rise varies between 0.7 and 1.8 m while the average fall is 1.1 m. The depth of the Shire River where it leaves the lake is at present about 3.5 m and, since at this level the river still only accounts for 20% of the water loss from the lake, a considerable change of level is necessary before a compensating change in outflow occurs. The lake is therefore in a state of delicate hydrological balance and runs of years of abnormally high or low rainfall result in

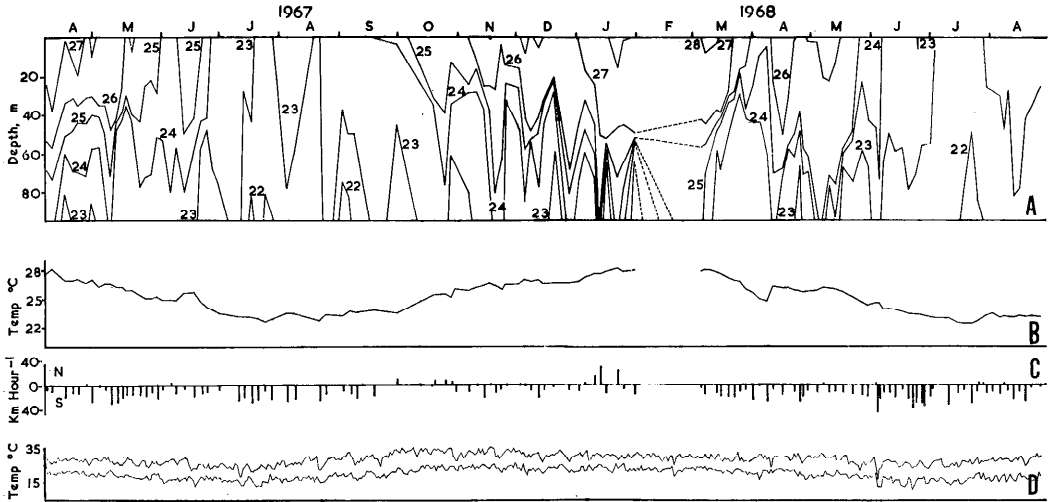


Fig. 2. A—Isotherm depths; B—temperature at 10 m; C—wind at the standard station off Monkey Bay; D—daily screen maximum and minimum air temperature at Monkey Bay over a 17-month period.

considerable variations of the surface level, the total range between 1900 and 1969 having been about 6 m. A barrage was constructed at Liwonde on the upper Shire River in 1965 and will be operated so as to maintain a certain minimum level consistent with the requirements of hydroelectric power generation. In addition to long term fluctuations of level, short term surface setups and seiches with an amplitude up to about 12 cm and periods of 6 and 24 hr occur, being most marked at the south end of the lake.

The lake occupies part of the southern end of the Rift Valley system and is to a large extent delimited by faults, particularly to the north and on the eastern coast. In these areas the shores are steep and depths in excess of 200 m are found close inshore (Fig. 1). At the southern extremity and along the southern half of the west coast the shoreline is more gently shelving. The maximum depth of 695 m is found toward the western shore about 45 km north of Nkhata Bay. From here the bottom rises gradually to north and south and, except for a ridge some 20 m high at 10°25'S, there is no trace of separate basins as in Lake Tanganyika. In further

contrast to Lake Tanganyika, where a depth of 200 m is found within 20 km of the southern extremity of the lake, in Lake Malawi such a depth is not encountered within 110 km of the southern end.

The present estimated annual catch of fish from the lake is quite small, being of the order of 21,000 metric tons in 1971. This is certainly an underestimate and is far short of the potential yield since some stocks are underexploited and others are untouched. However the distribution of fish is by no means uniform and echograms show stocks to be concentrated in the shallower marginal areas, in particular in the southeast arm. This recalls the situation reported for Lake Tanganyika by Coulter (1963) where inshore areas show relatively high productivity and the open lake is oligotrophic.

Methods

More or less regular observations have been made since March 1954, when the Joint Fisheries Research Organization selected a standard station close to that adopted by Beauchamp in a depth of about 400 m some 5.5 km offshore from Nkhata Bay in the middle section of the lake. Two

profiles have also been obtained near the deepest point of the lake some 37 km to the north of the standard station. In August 1962 the research center moved to Monkey Bay near the end of the peninsula between the southern arms of the lake, and from April 1963 until 1969 regular observations were made at a point about 4.5 km offshore at a depth of about 98 m. Observations at Nkhata Bay were discontinued in 1964. Some sporadic observations have been made during cruises, and some cruises have been made with regularly spaced stations. In May 1964, in conjunction with the work of Coulter (1968*a*) on Lake Tanganyika, temperature profiles were obtained from a series of stations along the length of the lake. Other series of profiles have been obtained in the southern part of the lake.

The observations at Nkhata Bay include temperature, chemical analyses, and net plankton. At first analyses were made for several ions (Jackson et al. 1963) but from 1957 were limited to pH, oxygen, and silicate since other nutrient ions were present in amounts too small to give meaningful results. At Monkey Bay only the temperature measurements have been continued on a regular basis, though some work was done on phytoplankton by a sedimentation method. Earlier observations were made with a Friedinger limnological sampling bottle and reversing thermometer; in 1961 these were replaced by a series of Knudsen oceanographic reversing water bottles with reversing thermometers attached. From time to time a thermistor sensitive to 0.02 °C was used, and since 1963 almost all observations have been made with this equipment. Readings with reversing thermometers were made at depth intervals of 5 or 10 m in the upper 100 m and thereafter at increments of 25 or 50 m. Thermistor readings at the Monkey Bay station are made at intervals of 2 m to the bottom at about 98 m. Since 1961 a nomographic correction has been applied to depth readings to allow for the inclination of the sampling wire, which may reach 35° in heavy

weather. Wind measurements at Monkey Bay were from the boat at the time of sampling using a Dwyer handheld patent windmeter.

Observations

The seasonal cycle of stratification

The Nkhata Bay observations are representative of the open area of the lake near the deepest part of the basin and show a thermal regime similar to that of the offshore areas of Lake Tanganyika (Coulter 1963, 1968*a, b*). Figure 3 shows temperature profiles made almost 9 years apart at the deepest point of the lake with one of Beauchamp's profiles for comparison. From the bottom to a depth of about 250 m the temperature is almost uniform. At 300 m the temperature had apparently risen from 22.45° to 22.56°. The temperature of 22.1° recorded in 1939 at this depth by Beauchamp (1953) indicates that this was probably a real rise, not an artifact of instrumental error, and that between 1939 and 1964 there was a gradual but steady warming at this level. At about 250 m there is a small but consistent thermal discontinuity, seen in Figs. 3 and 4. Since 1954 the water below this level has been anoxic and has contained free H₂S, although Beauchamp did on one occasion report the presence of small quantities of dissolved oxygen at 300 m. This deep hypolimnion is relatively rich in nutrient salts, but there is little difference in total ions, measured as conductivity, between this and the surface water (Beauchamp unpublished data; Jackson et al. 1963); hence the stability is probably maintained by the slight temperature difference rather than by increased concentrations of solutes.

In the upper 250 m an annual cycle of stratification occurs, illustrated by representative profiles in Fig. 4 and by a diagram of isotherm depths in Fig. 5. Complete mixing has never been observed, the nearest approach to a homothermal condition having been on 18 August 1958 after 8 days of continuous strong southerly winds, when the upper 80 m were homo-

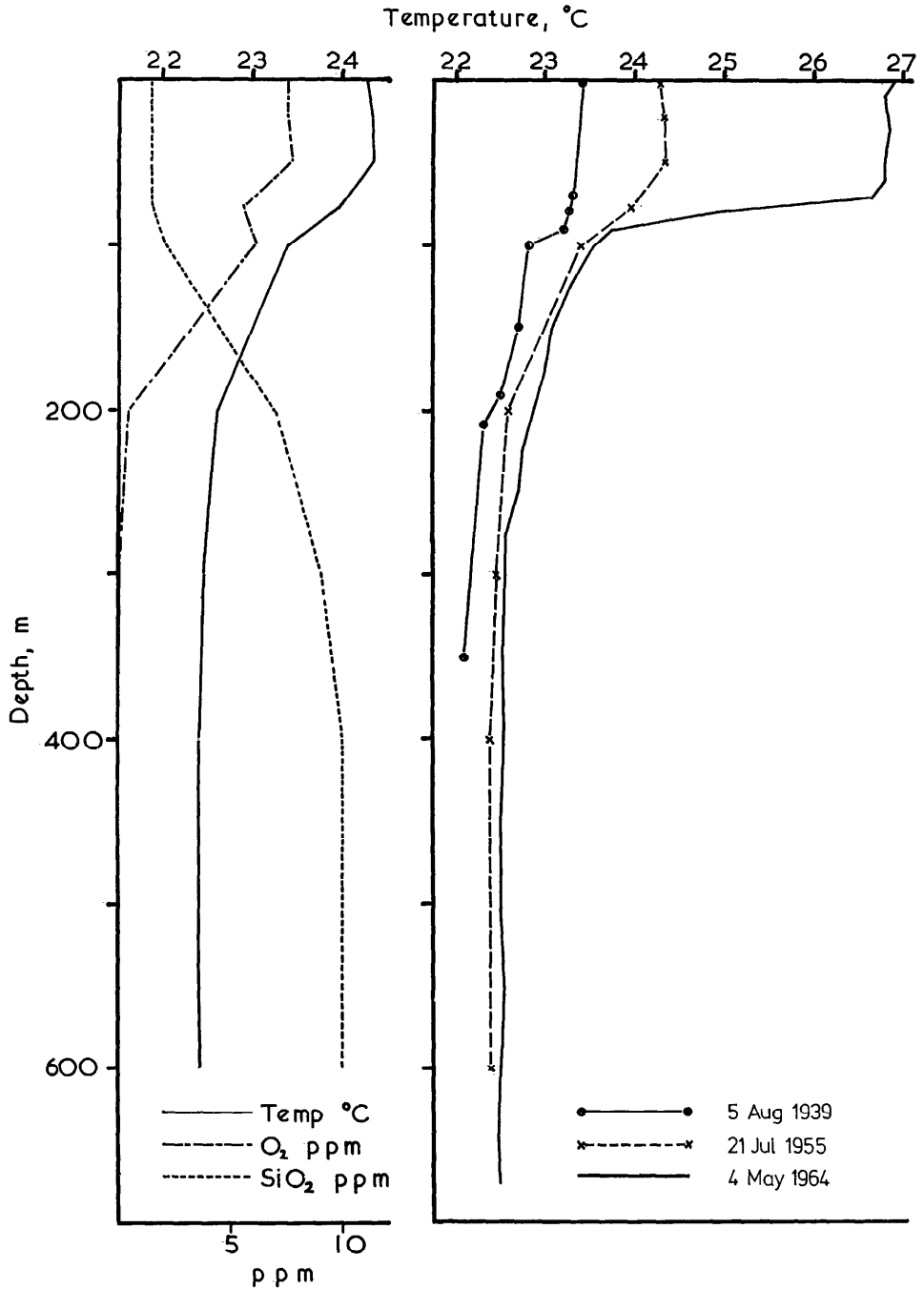
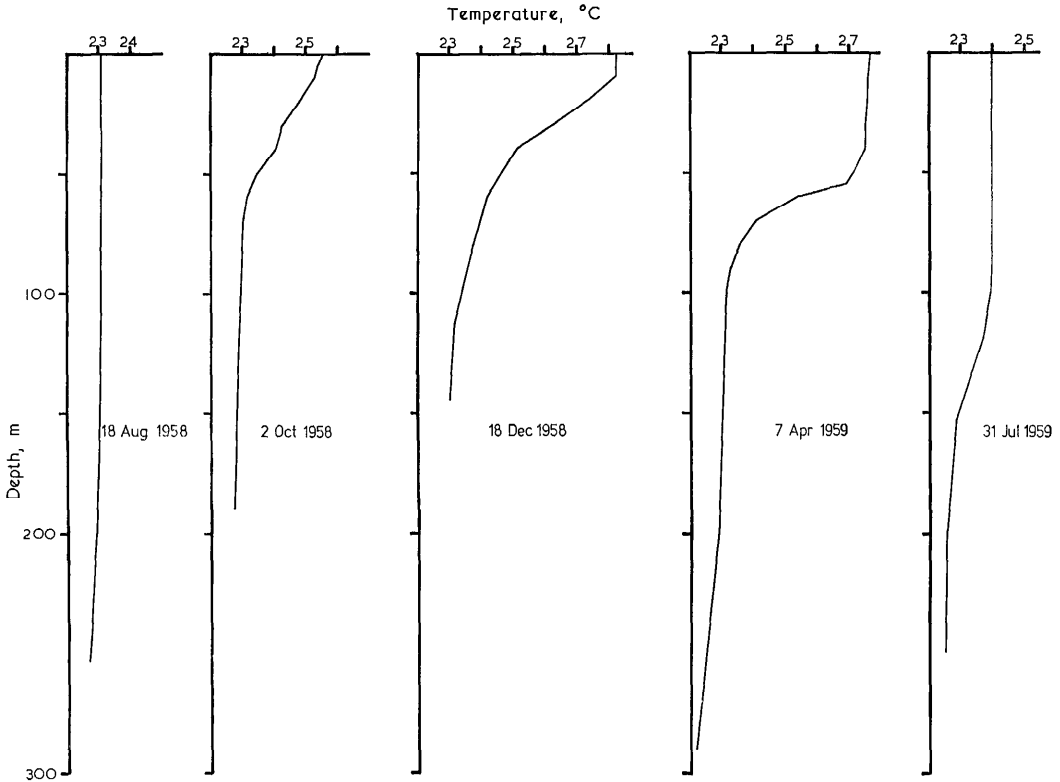


Fig. 3. Left—profiles of temperature, oxygen, and silica concentrations against depth at the deepest point of Lake Malawi (after Jackson et al. 1963). Right—temperature-depth profiles at a station 4 km off Nkhata Bay (after Beauchamp 1953) and at the deepest point of Lake Malawi 37 km north of Beauchamp's station showing warming of hypolimnion between 1939 and 1964.



Temperature profiles from deep station off Nkhata Bay

Fig. 4. Temperature-depth profiles showing seasonal development of stratification at the standard station off Nkhata Bay. Profile for 18 August 1958 shows closest recorded approach to a homothermal condition (after Iles 1960).

thermal at 23.08°C. The year 1958 was exceptional in the degree of surface cooling; in the other years between 1954–1963 the lowest surface temperature recorded at the standard station was 23.6°C.

While stratification is developing between September and December, temperature profiles usually show a series of gradients separated by more or less homothermal layers. Later, one major thermocline develops and moves deeper as the season progresses until, by the beginning of May, the whole upper 60 m may be homothermal at about 27°C. With the onset of the dry season, and of the southerly winds, cooling of the epilimnion begins and the thermocline is driven deeper.

The picture outlined above is somewhat idealized since in fact isotherm depths fluctuate considerably as the result of internal waves. These were first postulated by Beauchamp (1953), and an east–west tilt of the isotherms between Nkhata Bay and the opposite shore was demonstrated in January 1958 by Iles (1960). Eccles (1962a, b) demonstrated the existence on the upper thermocline of longitudinal undulations with an amplitude of up to 20 m.

At the station off Monkey Bay the annual cycle of events shown in Fig. 2 is basically similar to that in the upper 100 m at Nkhata Bay, but there are considerable differences of detail. Although for most of the year the surface temperature

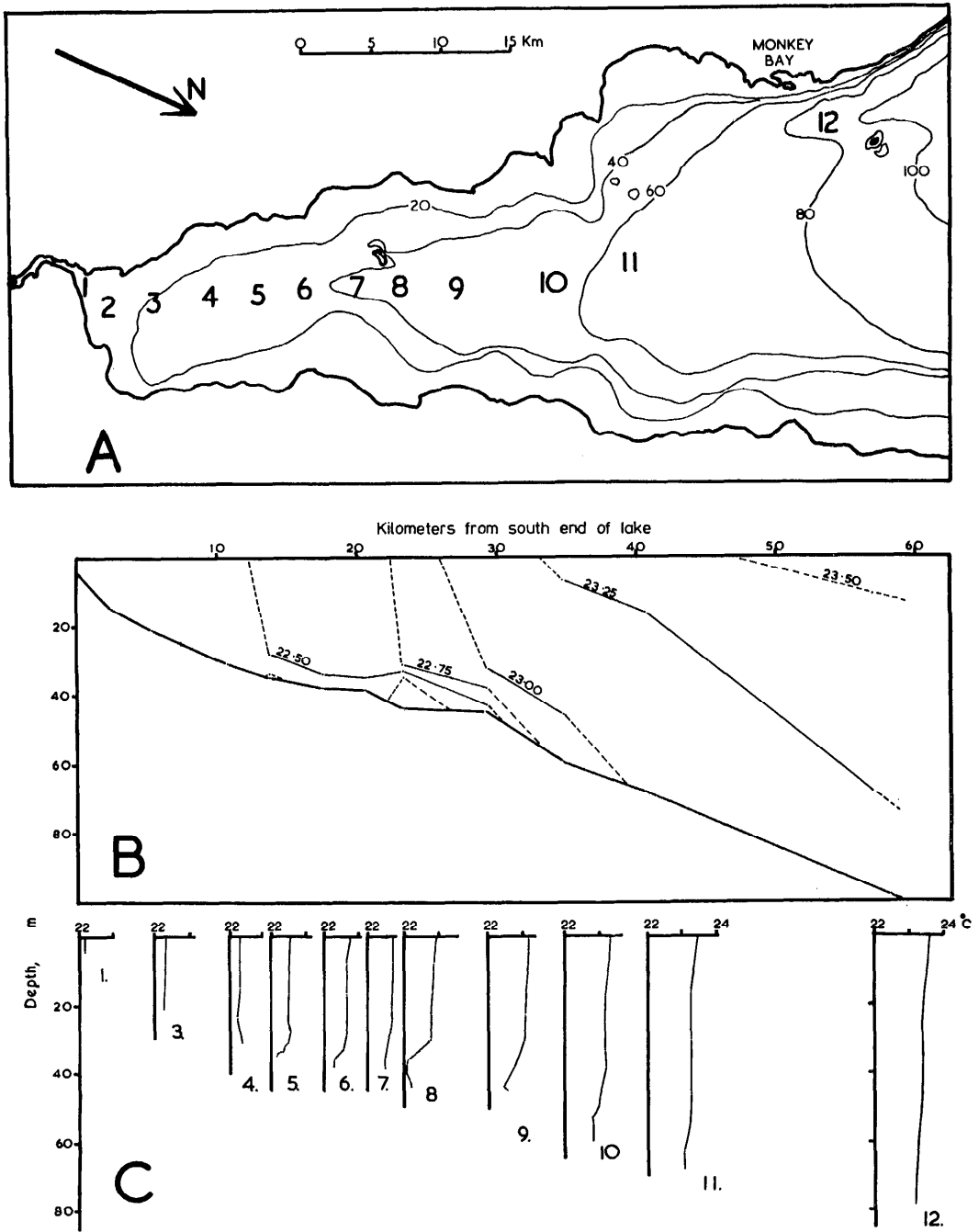


Fig. 6. A—Stations in the southeast arm; B—diagram of isotherm depths and temperature-depth profiles of individual stations on 30 July 1963, showing surface chilling of water at southern extremity; C—density current formed by sinking of chilled water.

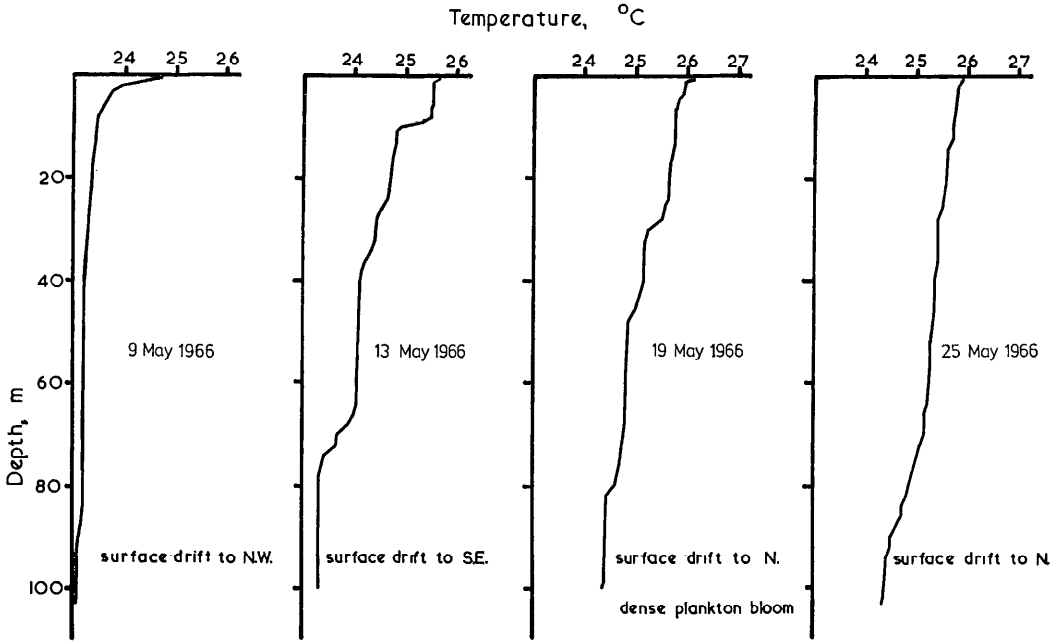


Fig. 7. Temperature-depth profiles at the standard station off Monkey Bay in May 1966 showing recovery of stratification over a 2-week period following upwelling during period of strong southerly winds.

on the bottom, Fig. 2 shows more or less regular oscillations of the thermocline with an amplitude of several tens of meters. The period of these oscillations tends to be shorter between December and February

when the epilimnion is warmest. At this time the period is about 20 days, becoming about 30 days by May. These oscillations appear not to be directly related to local wind and indeed are most regular in the rainy season when winds are variable in strength and direction. Upwelling of nutrient-rich water from the metalimnion may occur under the influence of strong wind stress, as in May 1966 when strong southerly winds in the early part of the month brought about upwelling off Monkey Bay. It was impossible to obtain data before the windy period, but Fig. 7 shows the recovery phase with the epilimnion rapidly returning. That this was in fact upwelling rather than local chilling is demonstrated by the fact that very dense blooms of phytoplankton were observed on 19 May and a scum of *Anabaena* collected in the lee of the launch several kilometers offshore. Such upwelling is not uncommon in the southeast arm during the windy season.

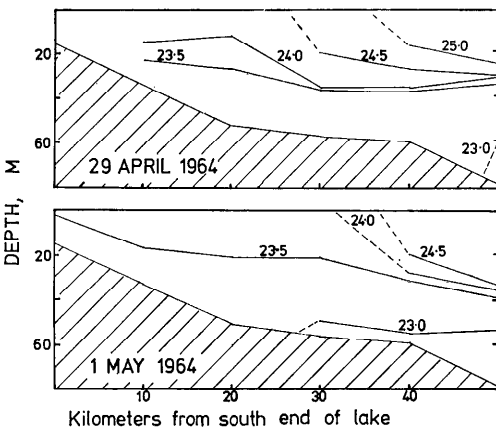


Fig. 8. Isotherm-depth profiles of southeast arm of Lake Malawi 2 days apart in April-May 1964 showing displacement of surface water and incursion of cool water along the bottom at the beginning of an upwelling period.

The apparent periodicity of the oscillations of the thermocline off Monkey Bay

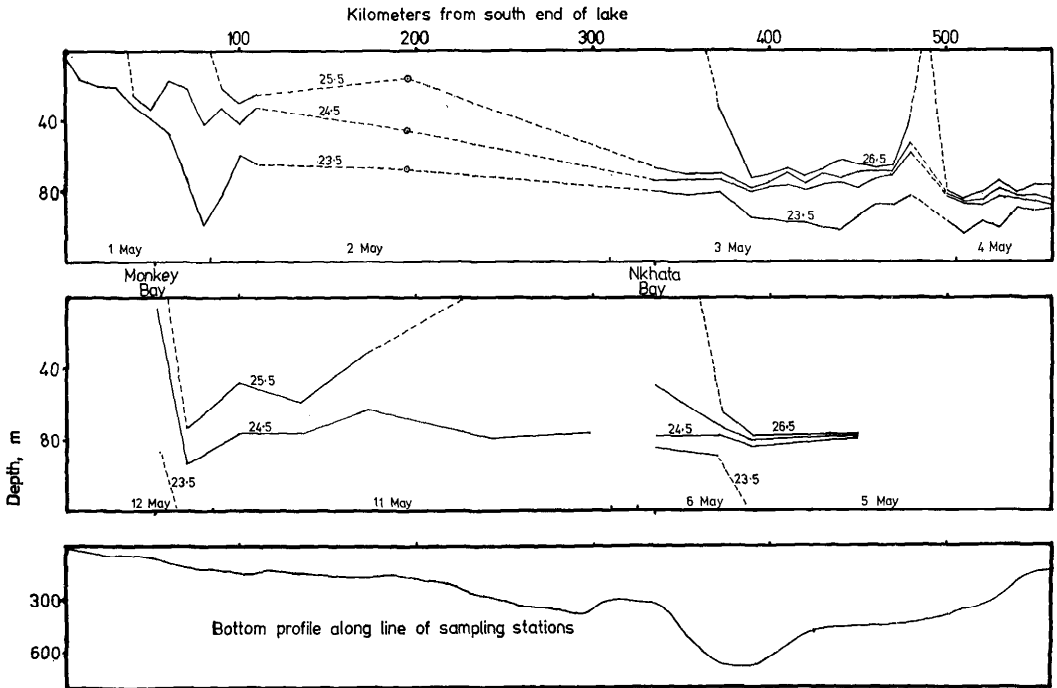


Fig. 9. Isotherm-depth profiles of Lake Malawi in May 1964 showing tilting of thermocline under the influence of southerly wind and recovery of level after cessation of wind.

and the occurrence of similar phenomena at the southern end of Lake Tanganyika led Coulter (1963) to suggest that they may be the effect of an overall tilting of the thermocline under the influence of an internal seiche. To test this hypothesis Coulter and I undertook longitudinal runs of both lakes in May 1964, measuring temperature profiles to a depth of 120 m at stations 10 km apart (Eccles 1965; Coulter 1968*b*). On Lake Malawi many of the stations near the middle of the lake had to be abandoned due to heavy weather and mechanical breakdown. However the results were sufficient to show a similar picture in both lakes. On Lake Malawi between 29 April and 1 May there was an incursion of cooler water from the metalimnion along the bottom (Fig. 8). This was accomplished by a general tilt of the thermocline in a northerly direction, the isotherms lying some 50 m deeper in the north than off Monkey Bay (Fig. 9), though by 12 May the isotherms at the south had

fallen to about the same level as those at the north. On the northward voyage an interruption of the thermocline was observed about 80 km from the north end of the lake. This was associated with a strong current shear between the surface and deeper water, the instrument wire being observed to enter the water across the direction of the wind. This may have been associated with separate surface circulation cells to the north and south of this point since the wind had been southerly in the southern part of the lake and at this station, but at the next station the wind was northerly. The mixing resulting from boundary effects between these cells could explain the relatively rich fisheries of the west shore in this area.

Currents

The current systems of the lake have not been studied, but sporadic observations and circumstantial evidence suggest that they may be of importance. In general

there appears to be a northerly drift on the western shore with a southerly return current of about 0.5 km hr^{-1} on the eastern shore. At times much stronger currents have been observed and on 2 February 1968 a wake was seen behind a buoy moored to a reef at a depth of 25 m about 7 km offshore from Monkey Bay; the current on this occasion was probably at least 1 km hr^{-1} . A similar current was observed south of Boadzulu Island in the southeast arm after a period of upwelling in April 1968, and again in early June 1968 a strong southerly current off Monkey Bay made it difficult to maintain course while trawling.

In addition to observational evidence for surface currents, the existence of profile-bound density currents is inferred from temperature data from the southeast arm. Probably considerable currents are generated near the bottom by the mass flow of the metalimnion and epilimnion into and out of this area in association with movements of the thermocline. Evidence for the existence of such currents is that reefs in the southeast arm are often surrounded by a moatlike depression in the bottom deposits, in which the soft ooze that covers most of the bottom in this area is replaced by a peculiar deposit consisting largely of fish bones and nodules. These occur in the ooze in small quantities and their greater abundance in the depressions around reefs is almost certainly the result of turbulence inhibiting the deposition of the finer particles of ooze.

Discussion

Although the temperature gradient at about 250 m is only some 0.01°C per meter, over 25 m it appears to form an effective barrier to mixing and thus to constitute a thermocline. The density difference across this thermocline is very small, but it probably persists due to the relative shortness of the cool season and to the mechanically inefficient transfer of wind energy through such a thick layer. Furthermore, the amount of energy required to bring about mixing against even a slight density

gradient is large where the layers concerned are several hundred meters thick.

The occurrence of chilling and of profile-bound density currents in the southeast arm suggests that this mechanism, first proposed by Talling (1963) to explain the stratification of Lake Albert and also considered by Coulter (1968*a*) to be a factor in the stratification of Lake Tanganyika, is in fact the reason for deep stratification in these lakes. The regular occurrence of these currents in Lake Malawi, and the fact that occasionally the cooling involves the whole southeast arm, at least as far north as Monkey Bay, means that large volumes of water must enter the hypolimnion every year. Since the hypolimnion itself is homothermal it must undergo mixing processes as the result of movements generated within it either by internal waves or by mechanical coupling with the metalimnion across the deep thermocline. Either of these processes would be expected to generate turbulence in the region of the thermocline which would gradually be driven deeper. That it does not in fact go deeper is due to the replenishment of the hypolimnion by cool density currents. Due to the form of the lake basin and to the direction of the prevailing winds it is probable that the main area of cooling is the southeast arm and, to a lesser extent, the southern half of the western shore. Although cooling takes place at such places as Nkhata Bay the nocturnal offshore winds along the steep coast in the area are so strong that an offshore surface current several meters thick is generated and cooled water is mixed into the epilimnion before it can sink.

The rise in the temperature at 300 m from 22.1°C observed by Beauchamp (1953) in August 1939 to the values of 22.45° in 1955 and 22.56° in 1964 (Fig. 3) indicates that there was a gradual warming of the hypolimnion over a period of 25 years. This must take place by mixing across the deep thermocline since the rate of heat flow through the lake floor, at about $30 \text{ cal cm}^{-2} \text{ yr}^{-1}$ (Von Herzen and

Vaquier 1967), is too low to have any significant effect on the heat budget of the lake. This warming suggests that the lake may overturn and there is some oral evidence that at least a partial overturn occurred in 1937 when a mass mortality of fish took place around Nkhata Bay. However, I feel that this was more likely to have been due to a local partial overturn or upwelling, rather than to a complete overturn. Had the latter occurred, the effects would have been dramatic due to fish mortalities consequent on the appearance of free H_2S over a large area of the lake. Beauchamp, whose 1953 paper reported data collected by him in 1939, could hardly have failed to have heard of the effects of such an occurrence, which would have impressed all the people on the lake. The temperatures of 23.4° at the surface and 22.95° at 75 m at Domira Bay in July 1939 are not inconsistent with stability, especially as the hypolimnion was then at about $22.1^\circ C$. The August 1946 figures of $21^\circ C$ at the surface and 20.75° at 20 m, recorded by Lowe and quoted by Beauchamp as indicating a possible overturn that year, were obtained at the extreme southern end of the lake and reflected local chilling.

It may be that, rather than the whole lake becoming homothermal at once, an overturn may take place fairly slowly so that there could be upwelling of anoxic water over a period of several weeks, which might allow the dissipation of H_2S and the oxygenation of the water at a rate sufficient to permit fish survival. Such a gradual overturn could occur as the result of a massive flow of cold water to the hypolimnion displacing quite large quantities of anoxic water, which may then mix fairly rapidly with the metalimnion where the H_2S would be oxidized. The mixed water, low in oxygen, might upwell in the southern part of the lake without causing mass mortalities. Such a mechanism seems possible in view of the fact that the main heat loss from the lake probably takes place by evaporative chilling, and that this is greatest at the windward end where the air is

relatively dry, having crossed the Shire Highlands. In the northern part of the lake the wind is moister, cloud amounts are greater, and evaporation is less, so that the surface temperature will not fall as low as at the south, and stratification may be maintained above the major part of the hypolimnion.

Internal waves appear to play a large part in nutrient cycling in Lake Malawi. Since in most years stratification above the hypolimnion does not break down completely they are an important mechanism in returning nutrients from the metalimnion to the epilimnion. Where the bottom is relatively gently sloping, quite small shifts in the level of the thermocline involve large horizontal displacements (Fig. 8) with resultant currents along the bottom. Turbulence associated with these currents will result in mixing between the metalimnion and the epilimnion and may also agitate the surface of the mud and release nutrients. In the open lake, currents associated with internal waves may also play a part in mixing processes, but this is apparently not as important as their effect at the lake margins. Upwelling under the influence of wind in the cool season is another important factor in the nutrient cycle, especially when the thermocline approaches the surface under the influence of an internal wave.

The nature of these internal waves is still unclear. The oscillations in thermocline depth at the southern end of the basin possess an apparent periodicity close to that calculated for a uninodal internal seiche in the absence of rotation. It seems likely, however, that the earth's rotation must be taken into account and that the undulations on the thermocline recorded by Eccles (1962*a, b*), which exhibited considerable amplitude offshore, may be associated with Kelvin-type internal boundary waves and internal Poincaré waves. A similar suggestion was made for Lake Tanganyika by Coulter (1968*b*). Many more extensive, detailed, and frequent temperature observations are needed to test these suggestions.

References

- BEAUCHAMP, R. S. A. 1953. Hydrological data from Lake Nyasa. *J. Ecol.* **41**: 226-239.
- COULTER, G. W. 1963. Hydrological changes in relation to biological production in southern Lake Tanganyika. *Limnol. Oceanogr.* **8**: 463-477.
- . 1968*a*. Thermal stratification in the deep hypolimnion of Lake Tanganyika. *Limnol. Oceanogr.* **13**: 385-387.
- . 1968*b*. Hydrological processes and primary production in Lake Tanganyika. *Proc. 11th Conf. Great Lakes Res. (Int. Assoc. Great Lakes Res.)* **1968**: 609-626.
- ECCLES, D. H. 1962*a*. An internal wave in Lake Nyasa and its probable significance in the nutrient cycle. *Nature (Lond.)* **194**: 832-833.
- . 1962*b*. Research results, Lake Nyasa. 2. Hydrology. *Annu. Rep. 11 (1961)*, p. 52-53. *Jt. Fish. Res. Organ. Gov. Printer, Lusaka.*
- . 1965. Hydrology. *Annu. Rep. Dep. Agr. Fish. 1964 (Fish. Res.) Part 2*, p. 19-24. *Gov. Printer, Zomba.*
- FEDERAL DEPARTMENT OF SURVEYS. Undated. Lake Nyasa pilot or sailing directions (with 16 associated charts). *Gov. Printer, Salisbury.*
- FUELLEBORN, F. 1900. Über Untersuchungen in Nyassa-See und in den Seen im nördlichen Nyassa-Land. *Verh. Ges. Erdkd. Berl.* **28**: 332-338.
- ILES, T. D. 1960. Activities of the organisation in Nyasaland. *D. Hydrology. Annu. Rep. 9 (1959)*, p. 11-12, 28-40. *Jt. Fish. Res. Organ. Gov. Printer, Lusaka.*
- JACKSON, P. B. N., T. D. ILES, D. HARDING, AND G. FRYER. 1963. Report on the survey of northern Lake Nyasa 1954-1955. *Jt. Fish. Res. Organ. Gov. Printer, Zomba.*
- PIKE, J. G. 1964. The hydrology of Lake Nyasa. *J. Inst. Water Eng.* **18**: 542-564.
- TALLING, J. F. 1963. Origin of stratification in an African Rift lake. *Limnol. Oceanogr.* **8**: 68-78.
- VON HERZEN, R. P., AND V. VACQUIER. 1967. Terrestrial heat flow in Lake Malawi, Africa. *J. Geophys. Res.* **72**: 4221-4226.

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