Biogeochemistry **61:** 291–307, 2002.

Biogeochemical response to physical forcing in the water column of a warm monomictic lake

WERNER ECKERT[1,*], JÖRG IMBERGER[2] and ANGELO SAGGIO[3]
*[1]Israel Oceanographic and Limnological Research, The Yigal Allon Kinneret Limnological Laboratory, P.O. Box 447, Migdal, 14950, Israel; [2]The Center for Water Research, University of Western Australia, Nedlands, 6907, Australia; [3]Departamento De Ecologia E Biologia Evolutiva, Universidade Federal De Sao Carlos, Sao Carlos, 13565-905, SP, Brazil; *Author for correspondence*

Received 22 November 2000; accepted in revised form 26 November 2001

Key words: Benthic boundary layer, Chemocline, Internal waves, Lake Kinneret, Microbial succession

Abstract. Based on microstructure measurements of temperature and horizontal current velocity the physical structure in the water column of Lake Kinneret was characterized as a five layer system consisting of a surface mixed layer, lower epilimnion, metalimnion, upper hypolimnion and benthic boundary layer. Using oxygen and hydrogen sulfide as natural chemical tracers, the time scale of chemical change was identified in relation to advection, mixing and biological processes. Rapid changes due to advection that took place on an hourly time scale were removed by referring the data back to the temperature of the water. Biological activity dominated the hydrochemical changes observed in the meta- and upper hypolimnion. These were expressed by DO depletion rates of 2.0 and 0.4 g m^{-2} d^{-1}, respectively. Vertical and horizontal mixing were shown to occur on a seasonal time scale. Once the chemical stratification process was completed the slow mixing through the benthic boundary layer became the limiting factor for subsequent reactions in the water column.

Introduction

Chemical stratification in mictic freshwater lakes proceeds in a sequence of physically and biologically mediated processes. It is well established that on an annual time scale, gradual surface water heating and wind action determine the thermal layering in the water column, and the associated succession of heterotrophic microbial processes act as the driving force for the chemical evolution in the deeper zones (e.g. Wetzel (1981)). While on a long time scale such an interplay between physics and biology has been studied (Imboden 1973 Livingstone 1988 Stefan and Fang (1994a, 1994b) Burns 1995) very little work has been carried out relating the chemical evolution in the water column of freshwater lakes to relatively fast physically driven phenomena such as wind induced internal waves, boundary mixing, turbulent mixing, meta- and hypolimnetic advection. Due to its regular shoreline development and bathymetry and predictable meteorological conditions, with daily westerly storms between May and October, warm monomictic Lake Kinneret provides ideal conditions for the simultaneous study of physical and chemical processes in the water column.

The chemical stratification in the water column of LK conforms to a distinct seasonal pattern that can be characterized by the evolution of dissolved oxygen (DO), nitrate and sulfide. During the time period of mixis (December–March) oxygen (> 8 mg l^{-1}) and nitrate (0.5 mg N l^{-1}) concentrations are high throughout the water column (Serruya 1978). With the on-set of thermal stratification in April, oxygen is gradually depleted in those zones that are isolated from atmospheric gas exchange. As oxygen is consumed denitrifying bacteria reduce nitrate before sulfate reduction becomes the dominant microbial process. The sulfide-enriched zone is separated from the water column above by a sharp chemocline. This process of anaerobiosis continues to the end of July at which time the chemocline rises to the metalimnion (Eckert and Trüper 1993).

The internal wave climate in the water column of LK during the time period of stratification was recently studied in detail by Antenucci et al. (2000). Their findings are summarized in a diagram showing schematically the physical structure in the water column for the time period April until October (Figure 1). Deviating from the classical stratification pattern, this diagram subdivides the water column into five zones: surface mixed layer (SML), lower epilimnion, metalimnion, upper hypolimnion and benthic boundary layer (BBL). Each of these layers can be identified by means of high resolution temperature profiling. The SML that results from wind induced surface turbulence is characterized by a uniform temperature. Separated from this well mixed zone by a distinct temperature step is the lower epilimnion where temperatures begin to decline and where mixing is intermittent. The relative thickness of both layers varies strongly over 24 hours depending on the intensity of wind action and the location of the sampling station. Below the metalimnion with its sharp temperature gradient resides the upper hypolimnion that is characterized by a very weak temperature gradient and weak mixing. This extends to a depth of 30 to 32 m at which point the water "feels" the bottom forming a BBL where temperatures again are uniform due to near bottom mixing (Nishri et al. 2000).

During the stratification period, the biologically mediated chemical changes proceed at different rates in different zones of the water column leading to chemically differentiated water strata defined by the rate of chemical change relative to the time scales associated with mixing and transport. This interplay of time scales in the metalimnion, upper hypolimnion and BBL regions is the focus of the present contribution. Using oxygen, nitrate and hydrogen sulfide as natural tracers and microstructure measurements of the physical conditions, the present study focuses on the effects of the physical forcing on the biologically mitigated chemical evolution of the water column of Lake Kinneret. In the following we present and discuss the physical and biogeochemical changes in the water column on the perspective of the time scale within these changes occur, while distinguishing between rapid changes caused by advection (T_a), microbially mediated intermediate changes (T_b) and long term changes due to mixing (T_m).

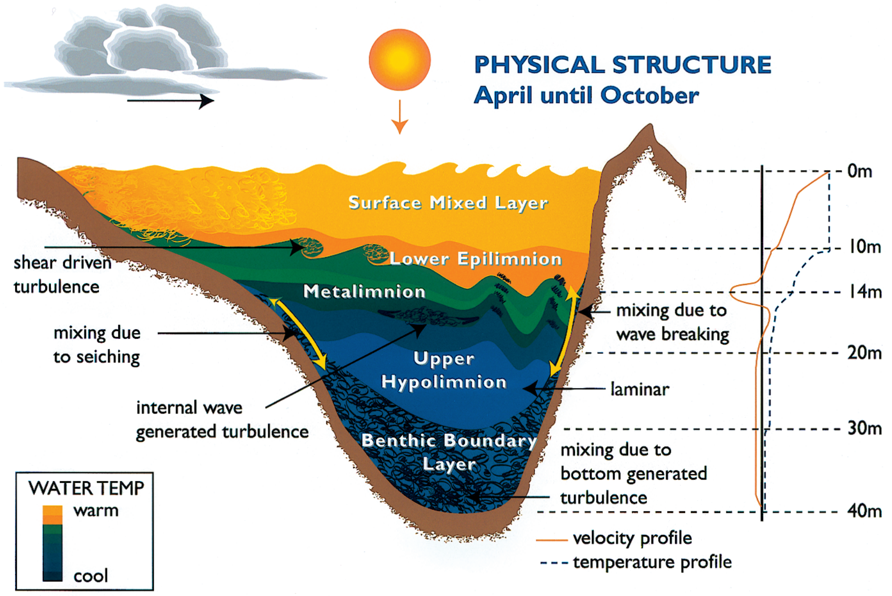


Figure 1. Physical structure of the water column of Lake Kinneret between April and October

Methodology

Study site

Lake Kinneret is a warm monomictic calcareous fresh water lake located in the northern part of the Afro-Syrian Rift valley. The lake has a surface area of 168 km^2 (22 km long by 12 km wide) and a total volume of $4{\cdot}10^9$ m^3. Average and maximum depths are 24 and 42 m, respectively. The Jordan River is the major inflow, while water pumped into the National Water Carrier constitutes the main outflow. Since maximum in water input and exploitation occur in different seasons, the lake altitude fluctuates between 209 and 213 m below mean sea level (Serruya 1978).

Analytical procedures

Physical and chemical data presented in this manuscript were collected from three stations including one at the center of the lake (T 4) one at a depth of 22 m (T 2) and one 30 m station (T5) close to the eastern shore (Figure 2). Information on dates and hours of profiling are listed below each station. Temperature data were collected continuously at each of these stations by means of thermistor chains at the vertical resolutions and sampling frequencies shown in Table 1.

Temperature, velocity and conductivity microstructures in the water column were measured by deploying the portable flux profiler (PFP) during several time series as indicated in Figure 2. The PFP is equipped with microsensors for tem-

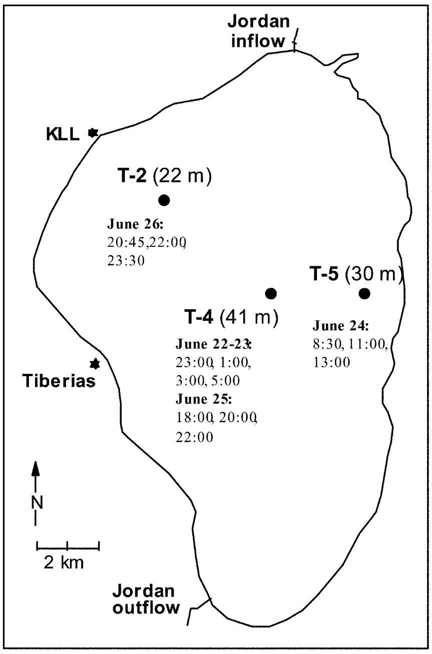


Figure 2. Thermistor chain locations, sampling stations, and sampling schedule for chemical profiling during the 1997 joint field experiment.

perature and conductivity and a laser Doppler velocity detector system. Vertical profiles of these parameters can be obtained with a resolution on a scale of millimeters and at a precision of $6{\cdot}10^{-4}$ °C for temperature, $2{\cdot}10^{-5}$ S m^{-1} for conductivity and $2{\cdot}10^{-3}$ m s^{-1} for current velocity (Imberger and Head 1994).

During PFP deployment, profiles of DO, pH_2S, pH and redox intensity (pe) were measured using the multiprobe developed by Eckert et al. (1990).

Results and discussion

At the time of the experiments, the five-layer system outlined in Figure 1 was forced by the regular westerly diurnal wind that occurred between 12:00 and 19:00 hrs. The wind, during this period, reached a magnitude between 8 m s^{-1} and 12 m s^{-1}. The response of the water column to this diurnal forcing was dominated by a near resonant first mode Kelvin wave the amplitude of which typically reached 4 to 5 m (range 8 to 10 m) (Serruya 1975 Antenucci et al. 2000); the strength of the stratification was such that the period of the Kelvin wave as it propagated anti-clockwise around the lake was close to 24 hours. Superimposed on this 24 hour response were also waves with periods at 12, 8 and 6 hours (Hodges et al. 2000). Beyond this was an apparent band of waves with periods between 6 hours and 15 minutes,

Table 1. Depth and sampling frequency of temperature sensors at the three stations.

T 2 (10 sec)	T 4 (5 min)	T 5 (20 sec)
1.0	1.0	4.0
4.0	4.0	6.0
6.0	6.0	8.6
7.0	8.0	11.2
8.0	9.0	13.8
9.0	10.0	16.4
10.0	11.0	19.0
11.0	12.0	20.0
12.0	13.0	22.0
13.0	14.0	24.0
14.0	15.0	26.0
14.5	16.0	27.0
15.0	17.0	
16.0	18.0	
17.0	19.0	
18.0	20.0	
19.0	22.0	
20.0	25.0	
21.0	32.0	
22.0	40.0	

which had a spectral amplitude proportional to ω^{-2} where ω is the frequency, and a range of modal responses. These waves were recently identified by Horn et al. (2000) as groups of non-linear waves resulting from the natural evolution of the basin scale waves as they steepen, disperse and decay over a variable basin topography.

Rapid changes: advection (T_a)

Our first profile series was measured at the central lake station (T4) from 23:00 on 22 June to 05:00 on 23 June, 1997 (Figures 3a–3d). Based on the high resolution temperature profiles from the PFP the thermal layering of the water column can be identified corresponding to the five-layer structure shown in Figure 1. The vertical temperature gradient (dt) amplifies the T difference measured on a millimetric scale to one meter and as such indicates zones of high and low T variability. In order to identify hypolimnetic changes in dt we have restricted the plotted scale to ±5 °C m^{-1}. The dt found in the metalimnion and at the boundary between SML and the lower epilimnion often exceeded this range.

The SML with a uniform temperature is distinguished from the lower epilimnion by a step in the temperature profile and by a maximum deflection of dt (upper dashed line in Figure 3). Following the weak temperature gradient in the epilimnion, a prominent drop in the temperature accompanied by highly variable dt char-

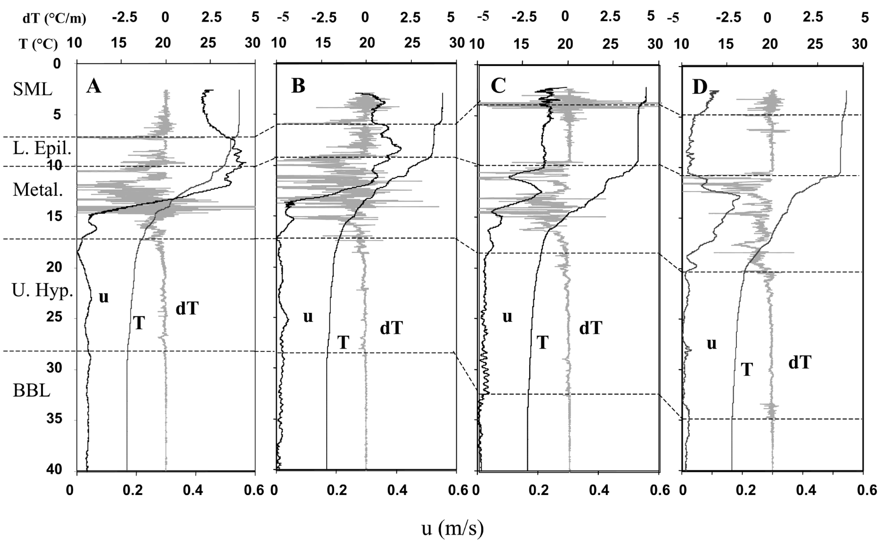


Figure 3. Temperature, temperature gradient and horizontal current speed measured by the PFP probe on June 22–23, 1997. A: 23:00; B: 01:00; C: 03:00; D: 05:00

acterizes the metalimnion. In the upper hypolimnion temperatures continue to decline at a much smaller rates with still some dt variability being visible. The small deflection in the hypolimnetic T-profile (lower dashed line in Figure 3) defines the upper boundary of the BBL where temperatures remain unchanged and where dt/m is < |0.03|.

Repeated profiling at T4 over the six-hour period revealed the short-term changes in this stratification pattern. The base of the SML rose from 7 m at 23:00 (Figure 3a) to 3 m at 3:00 (Figure 3c) while dropping to 5 m by 5:00 (Figure 3d). In the lower epilimnion temperatures increased from 27.5 °C at 23:00 to 29 °C at 5:00. In the same time interval, the temperature step to the metalimnion sharpened continuously (T curve below dashed line separating lower epi- from metalimnion). Both meta- and upper hypolimnion layers increased in thickness in contrast to the gradual decrease in the thickness of the BBL from 13 m at 23:00 (Figure 3a) to 7 m at 5:00 (Figure 3d). The isotherm displacement diagram drawn from thermistor-chain data from the same time period further illustrates the observed drop in the BBL (Figure 4). Over the same period the upper boundary of the BBL, which is marked by the 15.65 °C isotherm (dotted line in Figure 4), dropped from 29 m at 00:30 to 35 m at 05:00.

At 23:00, PFP measurements of horizontal current speed (Figure 3a) indicate an SML moving with a velocity of about 0.4 m s^{-1} and a jet structure between 7 m and 12 m where the velocity rose to 0.5 m s^{-1}. Such jets are typical for Lake Kinneret and were identified as a weak mode two signature (Antenucci et al. 2000). During the time period of the measurement (23:00 to 5:00) the current speed within the SML gradually decreased to 0.5 m s^{-1}. The maximum velocities in the metal-

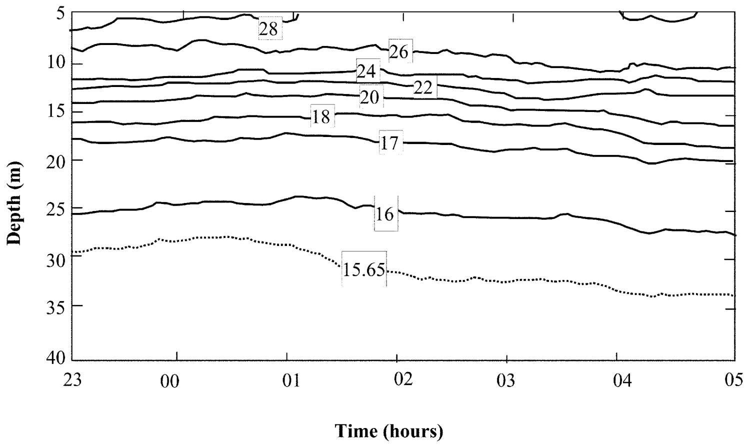


Figure 4. Isotherm displacement diagram, drawn from thermistor chain data measured in the water column at T4 during June 22, 23:00–June 23: 5:00.

imnetic mode 2 jet structure remained at 0.2 m s^{-1} and deepened from 10 m to 13 m (Figure 3a to 3d). By comparison very low current speeds ranging from 0.02 and 0.05 m s^{-1} prevailed in the upper hypolimnion and in the BBL over the whole period of the measurements.

After resolving the physical structure in the water column we can now proceed with the hydrochemical properties within each of the five layers. In Figure 5a–5d the chemical differentiation in the water column is expressed by DO, pe and total sulfide profiles while the outlines of shaded and non-shaded areas resemble the physically identified zones (Figure 3a–3d). At 23:00 the SML was supersaturated with regard to DO (13 ppm; 160% sat.). In the lower epilimnion DO concentrations declined from 13 to 5 ppm. In the metalimnion DO concentrations dropped further reaching 2 ppm at a depth of 12 m and remained constant below that that depth. The upper hypolimnion was characterized by DO concentrations fluctuating between 0.2 and 1.7 mg l^{-1}. The BBL was anoxic and separated from the upper hypolimnion by a sharp chemocline with pe values dropping by 3 to 4 units and with sulfide being present at concentrations ranging from 0 to 80 μmol l^{-1} while increasing towards the bottom.

During the six hour period covered by our profiling some distinct changes could be observed in the water column chemistry. The DO concentrations in the SML declined over time from 13 ppm at 23:00 to 11.4 ppm at 5:00 with concentrations being lowest near the surface. The depth of the initial oxygen gradient deepened within the lower epilimnion from 7 m (Figure 5a) to 9 m (Figure 5b) while at 5:00, it marked the border to the metalimnion (Figure 5d). After 1:00 a metalimnetic oxygen minimum was detected at 15 m (Figure 3b) descending to 16 m at 3:00 (Figure 3c) and to 18 m at 5:00 (Figure 3d). The DO concentrations in the upper hypolimnion fluctuated strongly leading to a differently shaped profile during each measurement. The chemocline depth dropped continuously from 29 m (23:00) to

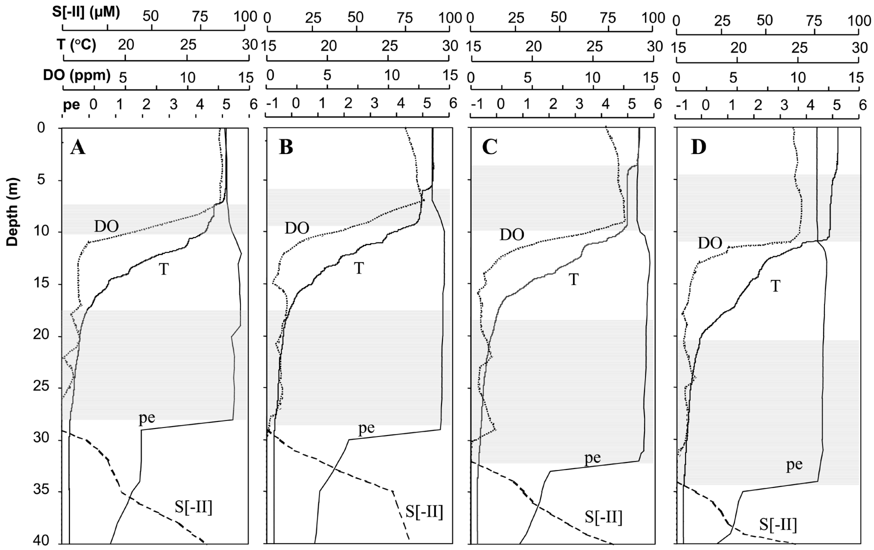


Figure 5. Temperature dissolved oxygen (DO), redox (pe) and total sulfide profiles measured at station T4 on June 22 and 23, 1997. A: 23:00; B: 01:00; C: 03:00; D: 05:00.

35 m (5:00) and as such followed closely the upper boundary of the BBL (Figure 3).

For the lower epilimnion and metalimnion the observations suggest that the most likely cause of changes in the DO profile was vertical advection caused by internal wave activity. To test this assumption the oxygen shown in Figure 5 was plotted against temperature rather than depth. As shown in Figure 6a this removed essentially all the variability in the metalimnion (19–23 °C). This hypothesis was further substantiated by the data from T5 taken on 24 June (Figure 6b), the data taken at T4 on 25 June (Figure 6c) and the data collected at T2 on 26 June (Figure 6d) all of which collapsed onto a single line once plotted against temperature. After June 22 (Figure 6a), metalimnetic DO data show an oxygen minimum in the 19–21 °C zone of the metalimnion (Figures 6b–6d).

Unlike station T4 where the DO exhibited no temporal trend (Figure 6a & 6c) our profile series from T5 and T2 revealed a distinct change with time. While profiling T5 (Figure 6b), hypolimnetic oxygen was absent at 8:30 but became detectable starting from 11:00 within a narrow zone centered at 17.5 °C with DO concentrations increasing from 0.6 at 11:00 to 1.0 mg l^{-1} by 13:00. A plausible explanation for this observation can be derived from the changes in the thermal structure in the water column during the time period of our profiling given by the isotherm displacement chart (Figure 7). The most significant event during our 4.5 h measuring period (marked by the arrows on the time scale) is a clearly defined step in the 19 and 21 °C isotherms (arrow) followed by an opening of the metalimnetic zone enclosed between the 17 and 19 °C isotherms. For a further discussion of this phenomena which was shown to be the result of a second mode long wave the reader

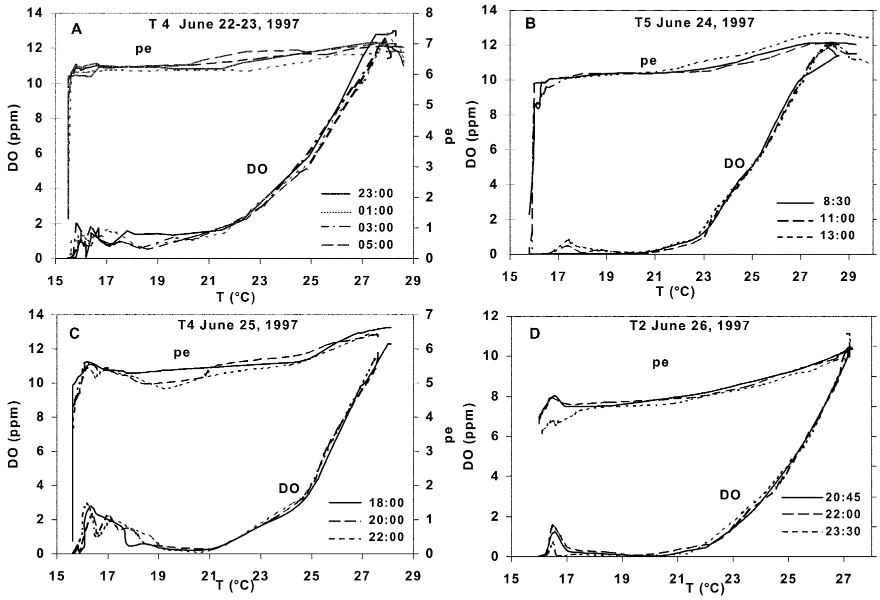


Figure 6. DO and pe vs T plot of data measured in the water column of Lake Kinneret between June 22 and 26 1997. A: Station T4, June 22–23; B: T5, June 24, C: T4, June 25; D: T2, June 26.

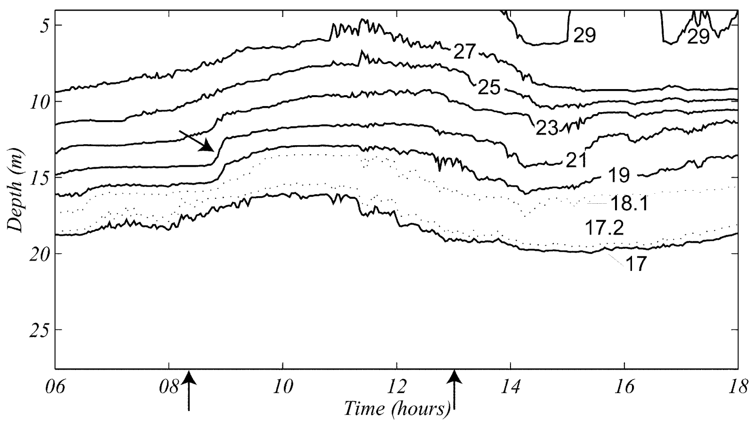


Figure 7. Isotherm displacement diagram from thermistor chain data collected at T5 on June 24, 1997. The time of profiling is indicated by the black arrows on the time scale. The dotted isotherms (17–18.1 °C) outline the hypolimnetic oxygen zone. The arrow indicates opening of the thermocline.

is referred to Antenucci et al. (2000). Delineating the zone where oxygen emerges by means of the 17 and 18.1 °C isotherms (dashed lines in Figure 7) it becomes obvious that the DO change occurs within the layer of thermocline opening and as such is the result of hypolimnetic advection.

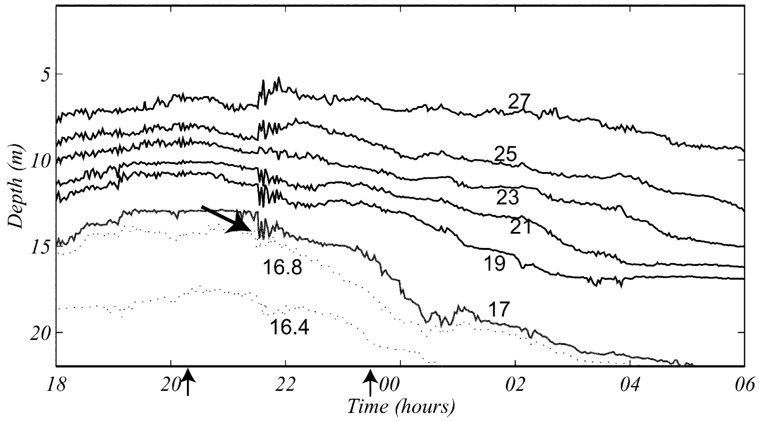


Figure 8. Isotherm displacement diagram from thermistor chain data collected at T2 between June 24 (18:00) and 25 (06:00) 1997. The time of profiling is indicated by the black arrows on the time scale. The dotted isotherms (16.4–16.8 °C) delineate the zone of the hypolimnetic oxygen maximum. The arrow indicates the occurrence of high frequency waves.

While at T5 DO in the upper hypolimnion increased over time the opposite was the case during our profile series carried out during late evening of June 26 at station T2 (Figure 6d). At 20:45 and 22:00 DO was measured in the zone between 16.4 and 17 °C with maximum DO concentrations of 1.3 and 1.6 mg l^{-1}, respectively. By 23:30 the DO peak reduced to 0.8 mg L^{-1}. During this time period the peak moved down in the water column from 15 m at 20:45 to 16 m at 22:00 and to 19 m at 23:30.

The most prominent feature in isotherm displacements from 1800 h 26 June–0600 h 27 June (Figure 8) is a 4 m drop of the 17 °C isotherm between 21:30 and 5:00 following the occurrence of high frequency waves (white arrow) as typically observed during the passage of an undulate bore (Antenucci et al. 2000). In the aftermath, the layer between the 17 and 19 °C isotherms widened while pushing down the zone below. This process explains the observed downward migration of the oxygen peak which appeared in a zone delineated by the 16.4 and 16.8 °C isotherms (dotted lines in Figure 8).

These changes suggest that the water in the upper hypolimnion is patchy in DO concentration. It appears that these patches are advected horizontally as a result of the velocities induced by the mode one seiching, as only vertical mode one waves have eigenfunctions which extend to the bottom (Antenucci et al. 2000). The variability of DO in the upper hypolimnion from station to station was of the order of 2 ppm (Figures 6a–6d). The distance between station T2 and T4 was about 2000 m and the velocity in the upper hypolimnion was about 0.03 m s^{-1}. Consequently, the expected variability in DO over 6 hrs should be about 0.7 ppm. This was indeed observed (Figure 6). These time scales imply patches of oxygen of the order of 6000 m in length. In the metalimnion the water was being advected rapidly horizontally by the mode 2 and 3 motions (Antenucci et al. 2000), while being heaved up and down by the vertical mode 1 internal wave motion.

In contrast to the variability found in the upper hypolimnion the chemical conditions in the BBL, characterized by the lower pe values (Figures 6a–6c) do not alter on the short time scale. Furthermore, the observed 4 m drop of the chemocline (Figure 5) coinciding with the displacement of the 15.65 °C isotherm characterizing the upper boundary of the BBL (Figure 4) shows that the BBL had separate biogeochemical properties to those in the upper hypolimnion.

Biologically mediated (T_b) and mixing (T_m) time scales

Besides the rapid hourly changes in the water column the comparison between DO profiles measured on different days suggests some chemical changes taking place on a time scale of several days. For instance the metalimnetic DO concentrations in the 19–21 °C zone at T4 decreased from ca. 1 mg l^{-1} on 22 June (Figure 6a) to zero on 25 June (Figure 6c).

The phenomenon of a metalimnetic oxygen minimum has been reported frequently during the stratification process of mictic lakes (Ohle 1951 Shapiro 1960). In case of Lake Kinneret this was demonstrated during three annual lake cycles revealing a maturing time of several weeks (Eckert 1989). At this stage the most plausible hypothesis for this long term process is enhanced biological activity in this specific zone, possibly due to the accumulation of detrital material when sinking into colder water (Eckert and Trüper 1993 Kufel and Kalinowska 1997) or from intrusions from the boundary (Ostrovsky et al. 1996).

Of particular interest is the presence of DO in the upper hypolimnion with concentrations varying between 0.2 and 3 mg L^{-1} (Figure 6) in the 15.5–19 °C zone. Our interpretation is that this residual entrapped oxygen from the time period of mixis. This hypothesis is further substantiated by the presence of prestratification nitrate concentrations (400 μg N l^{-1}, Figure 9) in this layer. Denitrification becomes the dominating microbial process only once DO levels drop below 250 μg l^{-1} (Bonin et al. 1989).

In the following we have quantified biological DO consumption from measurements carried out between June 20 and 30, 1997. Starting from the assumption that, due to the high current speed in the metalimnion vertical mode 2 induced jet (Antenucci et al. 2000) the chemical conditions in this zone are relatively homogeneous, we can calculate the total metalimnetic oxygen pool from DO profiles by integrating the DO concentrations within a water column over one square meter delineated by the 19 and 23 °C isotherms at different stations. From June 20 until 26 (Figure 10), oxygen decreased at a rate approximating 2 g m^{-2} d^{-1} reflecting enhanced biological activity in the metalimnion explaining the occurrence of the metalimnetic DO minimum. Starting from a DO pool of 13 g m^{-2} we obtain a biological turnover time of T_b = 7 days for the lower metalimnion. The decline in DO uptake rates between June 26 and 30 can have two possible reasons: a drop in the abundance of organic matter or a shift of the heterotrophic microbial community to other electron acceptors due to adaptation to low oxygen concentrations.

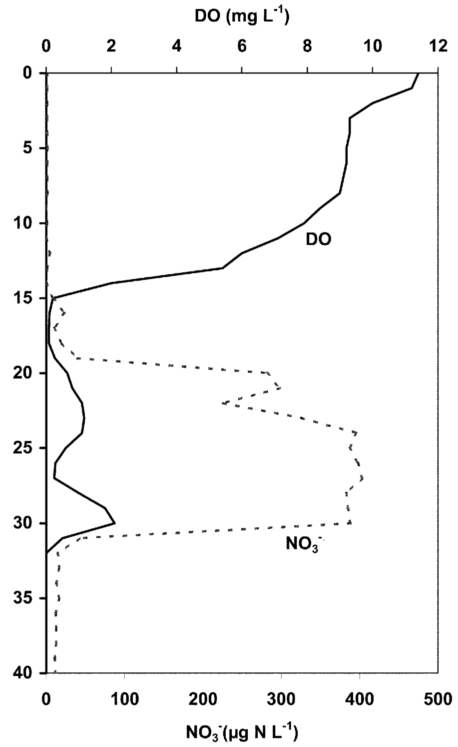


Figure 9. Dissolved oxygen and nitrate profile measured at T4 on June 30, 1997.

The change in the DO pool in the upper hypolimnion of station T4 (15.5–19 °C zone) is shown in Figure 10. Due to rapid time changes in the oxygen concentrations, the upper hypolimnion data are based on average values from our two profile series at T4 on June 22 and 25 together with two single DO profiles measured on June 22 (not shown) and June 30 (Figure 9). The plot shows that hypolimnetic oxygen decreased at a rate of 0.44 g m^{-2} d^{-1} corresponding to a oxygen depletion time of T_b = 36 days starting from an oxygen pool of 16 g m^{-2}.

In LK, directly measured vertical mixing coefficients (K_v) in the metalimnion and upper hypolimnion are 3.5×10^{-5} and 10^{-6} m^2 s^{-1}, respectively (Saggio and Imberger 2001). As such the time scale for vertical mixing (T_m (v)) can be calculated as:

$$T_m(v) = L_p^2 K_v^{-1}$$

with L_p = length path (10 m). This leads of vertical mixing rates in the metalimnion and in the upper hypolimnion of 33 and 1100 days, respectively.

By contrast, horizontal mixing is most likely sustained by shear dispersion arising from shear of the internal wave field (Stocker et al. 2000). In the metalimnion where current velocities are strong an horizontal mixing coefficient of K_h = 10

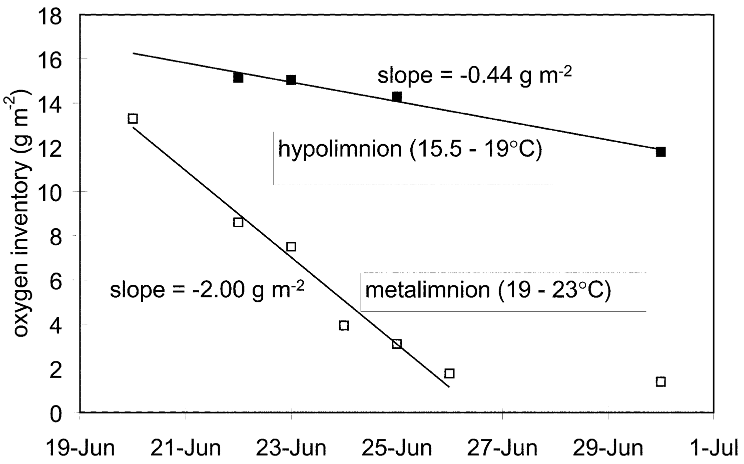


Figure 10. Time change in the metalimnetic and hypolimnetic dissolved oxygen inventories calculated from DO profiles measured between June 19 and 30, 1997.

$m^2\ s^{-1}$ was found empirically (Stocker, pers. communication). In the upper hypolimnion current speeds are one order of magnitude smaller reducing K_h to 1 $m^2\ s^{-1}$. The horizontal mixing timescale T_m (h) is then given by:

$$T_m(h) = L_p^2 K_h^{-1}$$

This implies that it requires 42 days (metalimnion) and 420 days (upper hypolimnion) to mix a tracer across the width of the lake (L_p = 6 km). These figures are only indicators but they illustrate that the transport by either vertical or horizontal mixing is $\sim$ 1 month in the metalimnion and > 1 year in the upper hypolimnion. This is an intuitively obvious result as we observe in such lakes that the temperature of bottom waters changes only little over a season, unless there is a deep cold underflow.

Conclusions

The present study has shown that there was a clear partition of time scales in Lake Kinneret at the time of measurement for the variables under consideration: DO, pe, and pH_2S. The largest variability resulted from the advection (T_a) by the internal wave induced flow field. This involved time scales from hours to about one day. Although the variability due to this advection was the largest, it could be removed effectively by referencing the data back to the water temperature. This worked well within the metalimnion and upper hypolimnion where temperature is conserved over 24 hours or longer.

The second class of variability, with a time scale ranging from days to weeks (T_b) was clearly due to biologically mediated reactions. These processes are the

Table 2. Time scales of physical and biological processes in metalimnion and upper hypolimnion of Lake Kinneret (a = advection, b = biology, m = mixing)

	T_a	T_b	T_m (horizonal)	T_m (vertical)
Metalimnion	0.4 d	7 d	42 d	33 d
Upper Hypolimnion	2.4 d	36 d	420 d	1100 d

cause for the chemical differentiation in the water column and include DO depletion by respiration, denitrification and sulfate reduction.

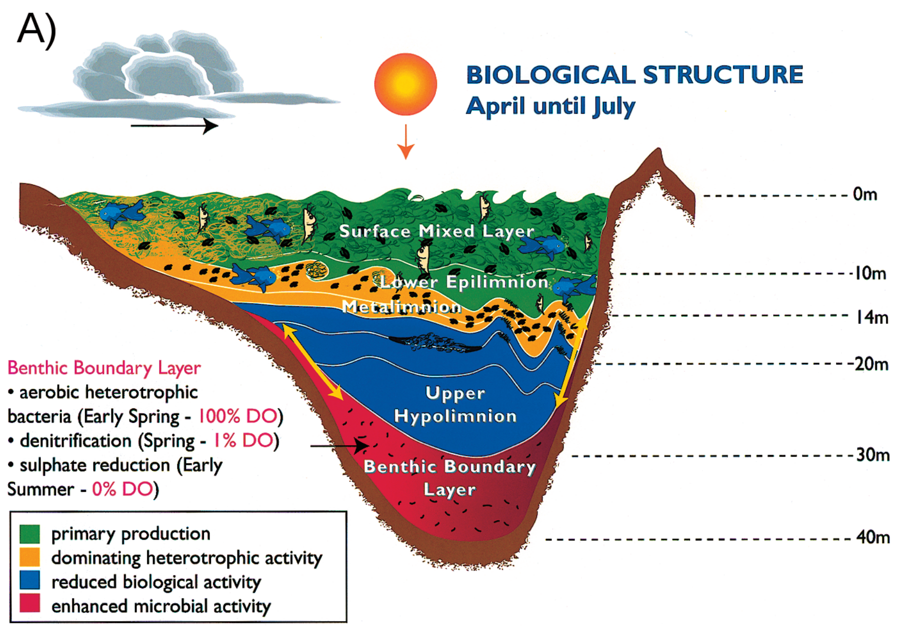
On the other hand vertical ($T_{m\ (v)}$) and horizontal mixing ($T_{m\ (h)}$) were shown to occur on a seasonal time scale. This results in a higher hierarchy of time scales:

$$T_a \ll T_b < T_{m(h)} \sim T_{m(v)},$$

and implies critical importance of the seasonal time scales. Once the biochemical reactions have gone to completion (on a time scale much faster than the seasonal time scale), slow mixing through the benthic boundary layer becomes the limiting factor for subsequent reactions. The different scales found with the present study for metalimnion and upper hypolimnion are summarized in Table 2.

With this information we are now able to describe the sequence of events during the chemical stratification process in the water column of Lake Kinneret as being due to the interplay between physical forcing and biological activity. We have condensed our findings into an overall picture by means of two diagrams showing the biological (Figure 11A) and chemical structure (Figure 11B) in the lake. In relation to the physical layering (Figure 1), water column biology and chemistry can be described as follows:

- The SML of a variable wind related thickness is characterized by turbulent mixing and high biological activity with strong daily fluctuations due to primary production. This leads to oxygen supersaturation during daytime counterbalanced by DO uptake and atmospheric gas exchange at night.
- The lower epilimnion, with the thickness which changes in relation to the SML where temperatures begin to decline. Biological conditions are strictly oxic but declining DO concentrations in parallel to the temperatures indicate the influence of heterotrophic microbial activity.
- The metalimnion as the zone of maximum thermal stratification and most prominent oxygen gradients. During early summer high heterotrophic microbial activity causes the formation of a local DO minimum in the lower part of this zone.
- In the laminar upper hypolimnion strongly reduced biological activity leads to the presence of residual oxygen patches and prestratification nitrate levels until early summer. These patches are advected around at current speeds < 0.05 m s^{-1} while their oxygen content is reduced at a rate of 0.44 g m^{-2} d^{-1} by biological activity.



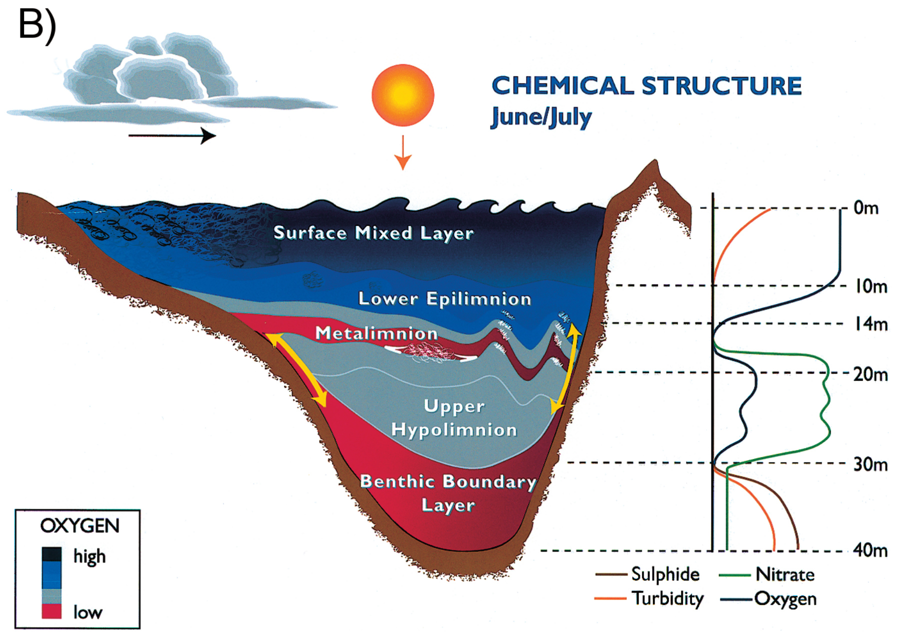


Figure 11. A) Biological structure in the water column of Lake Kinneret for the time period April until July due to the physically mediated zonation. B) Chemical structure in the water column of Lake Kinneret during early summer as result of the interplay between physical forcing and biological processes.

- A strongly enhanced microbial activity characterizes the BBL where oxygen and nitrate are depleted first followed by sedimentary sulfide release.

Due to the continuation of daily westerly storms one can assume that the physical structure (Figure 1) remains unchanged until October when the cooling process of the surface water starts.

Acknowledgements

This study was part of a joint field experiment between the Center for Water Research (CWR) of the University of Western Australia (Perth) and the Kinneret Limnological Laboratory (KLL) The field trip was financed by the Center for Water Research (University of Western Australia). The Israel Ministry for Infrastructure supported the KLL activities in this study (research grant # 97-17-035). We wish to thank the skippers James Easton and Meir Hatab for their support in the field and Aminadav Nishri for providing the nitrate data. Finally we appreciate the valuable comments by three anonymous reviewers.

References

Antenucci J.A., Imberger J. and Saggio A. 2000. Seasonal evolution of the basin-scale internal wave field in a large stratified lake. Limnol. Oceanogr. 45: 1621–1638.

Bonin P.M., Gilewicz A. and Bertrand J.C. 1989. Effects of oxygen on each step of denitrification on *Pseudomonas nautica*. Can. J. Microbiol. 35: 1061–1064.

Burns N.M. 1995. Using hypolimnetic dissolved oxygen depletion rates for monitoring lakes. New Zealand Journal of Marine and Freshwater Research 29: 1–11.

Eckert W. 1989. Quantitative investigations on the microbially mediated redox chemistry of the metalimnetic sulfur system in Lake Kinneret, Israel: The influence of a bloom of phototrophic bacteria. PhD Dissertation, University of Bonn, Germany.

Eckert W., Frevert T. and Trüper H.G. 1990. A new liquid-junction free probe for the in situ determination of pH, pH_2S and redox values. Water Res. 24: 1341–1346.

Eckert W. and Trüper H.G. 1993. Microbially-related redox changes in a subtropical lake 1. In situ monitoring of the annual redox cycle. Biogeochemistry 21: 1–19.

Hodges B.R., Imberger J., Saggio A. and Winters K.B. 2000. Modeling basin-scale internal waves in a stratified lake. Limnol. Oceanogr. 45: 1603–1620.

Horn D.A., Redekopp L.G., Imberger J. and Ivey G.N. 2000. Internal wave evolution in a space-time varying field. Journal of Fluid Mechanics 424: 279–301.

Imberger J. and Head R. 1994. Measurement of turbulent properties in a natural system. Proc. Fundam. Adv. Hydraulic Measur. Exp. Buffalo, New York USA, Aug. 1994: 1–20.

Imboden D.M. 1973. Limnologische Transport- und Nährstoffmodelle. Schweiz. Z. Hydrol. 35: 29–68.

Kufel L. and Kalinowska L. 1997. Metalimnetic gradients and the vertical distribution of phosphorus in a eutrophic lake. Archiv Fur Hydrobiologie. 140: 309–320.

Livingstone D.M. 1988. Einfluβ externer physikalischer Faktoren auf das Sauerstoffregime des Aegerisees. PhD Dissertation, Univ. Zürich.

Nishri A., Imberger J., Eckert W., Ostrovosky I. and Geifman J. 2000. The physical regime and the respective biogiochemical processes in lower water mass of Lake Kinneret. Limnol. Oceanogr. 45: 972–981.

Ohle W. 1951. Der labile Zustand ostholsteinischer Seen. Fischereiwirtschaft 12: 1–8.

Ostrovsky I., Yacobi Y.Z., Walline P. and Kalikhman I. 1996. Seiche induced mixing: its impact on lake productivity. Limnology Oceanography 41: 323–332.

Saggio A. and Imberger J. 2001. Mixing and turbulent fluxes in the metalimnion of a stratified lake. Limnol. Oceanogr. 46: 392–409.

Serruya S. 1975. Wind, water, temperature and motions in Lake Kinneret: General patterns. Verh. Int. Verein. Theoret. Angew. Limnol. 19: 73–87.

Serruya C. (ed.) 1978. Monographiae Biologicae. Dr W. Junk Publishers, The Hague, Lake Kinneret, 502 p.

Shapiro J. 1960. The cause of a metalimnic minimum of oxygen. Limnol.Oceanogr. 5: 216–227.

Stefan H.G. and Fang X. 1994a. Model simulations of dissolved oxygen characteristics of Minnesota lakes: Past and future. Environ. Managem. 18: 73–92.

Stefan H.G. and Fang X. 1994b. Dissolved oxygen model for regional lake analysis. Ecol. Model. 71: 37–68.

Stocker R., Imberger J. and D'Alpaos L. 2000. An analytical model of a circular stratified rotating basin under the effect of periodic wind forcing. In: 5th International Symposium on Stratified Flows, July 2000. ISSF, Vancouver, pp. 387–392.

Wetzel R. 1981. Limnology. Saunders, New York.