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Internal wave-induced changes in the chemical stratification in relation to the thermal structure in Lake Kinneret

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Introduction

During its annual cycle, the water column of thermally stratified lakes undergoes chemical differentiation depending on the trophic state (WETZEL 1983). Because of microbial succession, eutrophic lakes typically develop anoxic, sulphide-enriched hypolimnia. Warm-monomictic Lake Kinneret (LK) belongs to this category. After the onset of stratification in April, hypolimnetic oxygen is depleted by May/June followed by steadily increasing hypolimnetic sulphide concentrations. During summer and fall, the hypolimnion becomes continuously enriched with phosphate and ammonium (SERRUYA 1978). Further characteristics of LK during the summer months are daily westerly storms leading to strong internal seiche activity. The thermocline then oscillates in a 24-h rhythm with amplitudes reaching 10 m (SERRUYA 1975, HODGES et al. 2000). Recent investigations, based on transects and long-term measurements, displayed the diurnal variability of the hypolimnion location during the passing of seiche events (NISHRI et al. 2000, ECKERT et al. 2002). Of particular interest was the spatial and temporal evolution of the benthic boundary layer where nutrient levels were at all times higher than in the upper part of the hypolimnion.

The daily variability found with regard to the hypolimnion movement is critical for routine sampling procedures in those zones that become temporarily anoxic. The question arises: How representative are results gained from the routine analysis of water samples from fixed depths? The present study was designed to follow the wind-induced local and temporal vertical patchiness in the water column of LK and to verify the meaningfulness of sampling results under these variable conditions.

Methodology

Study site
Lake Kinneret is a warm monomictic calcareous freshwater lake located in the northern part of the Dead Sea Rift Valley. The lake has a surface area of 168 km^2 (22 km long × 12 km wide) and a total volume of 4×10^9 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 maxima in water input and exploitation occur in different seasons, the lake altitude fluctuates between –209 and –213 m below mean sea level.

There is a large difference between the chemical composition of the hypolimnion and the epilimnion of LK (SERRUYA 1978). During the stratified period, the epilimnion is N and P limited, in contrast to the nutrient-enriched hypolimnion, with N and P concentrations ranging from 0.3 to 1.5 mg L^{-1}, and from 0.002 to 0.150 mg L^{-1}, respectively.

Analytical procedures
Between winter and fall 1999, two 24-h surveys were carried out, one on April 29–30 during the period of the algal spring bloom and one during the stratified July 8–9 period. The surveys were carried out at locations where the water depth was 28–29 m, in order to ensure that measurements were taken in a zone that was well stratified and exposed to internal wave intensity. Using a combination of in-situ electrode techniques and the analysis of water samples pumped from the target depth, at a resolution of 1 m, the following parameters were measured in parallel in the water column:

- temperature, dissolved oxygen (DO) and pH – by means of a custom-made multiprobe designed especially for deployment in sulphide-enriched aquatic systems (ECKERT et al. 1990);
- turbidity – by means of a Hydrolab multiprobe (during the second survey);
- phosphate and nitrate – by flow injection spectrometry (Lachat);
- chlorophyll *a* (chl *a*) and the taxonomic composition of the algal assemblages – by delayed-fluorescence spectrometry, a technique that can distinguish between cyanophytes, cryptophytes,

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chlorophytes, diatoms and dinoflagellates (GERHARDT & BODEMER 2000).

Results and discussion

During the first survey (April 29–30, 2000), the water column was thermally stratified, with water temperatures ranging from 24.5 (surface water, 15:00 h) to 17.6 °C (near bottom, 22:00 h; Fig. 1a). The thickness of the epilimnion remained at 10 m while that of the meta- and hypolimnion indicated intensive internal wave activity. In the early morning of April 29 the metalimnetic temperature gradient zone reached to the bottom. A hypolimnion, here delineated by the 18 °C isotherm, became detectable after 10:30 h, rising to a depth of 20 m by 19:00 h and declining gradually to 26 m depth until 30 h (6:00 h, April 30).

The thermal structure is mirrored by the DO isopleths (Fig. 1b). While the whole water column was oxic during the first profile measured at 8:00 h, DO profiles confirmed that the hypolimnion development with the oxycline closely followed the 18 °C isotherm. Dissolved oxygen concentrations in the upper 10 m of the water column were always greater than 10 mg L^{-1}, reaching maximum values (>13 mg L^{-1}) at a depth of 3 m between 13:00 h and 16:00 h. Contrary to SRP (not shown), with low concentrations (<10 µg L^{-1}) throughout the water column, nitrate concentrations covered a wide range (7–140 µg N L^{-1}; Fig. 1c). The pattern of the nitrate isopleths corresponds to that found with DO in the epilimnion, with ca. 100 µg N L^{-1}, and the hypolimnion where concentrations dropped below 10 µg N L^{-1}. Metalimnetic nitrate concentrations fluctuated between 120 and 140 µg N L^{-1}, showing two distinct peaks in 15 m at 14:00 h and 21:00 h. The reasons for this distribution are denitrification in the hypolimnion and enhanced assimilative N-uptake in the epilimnion. The metalimnetic patchiness can be explained by the advection of pockets with residual nitrate from the period of mixis. Similar metalimnetic jet structures were identified in the past during physical studies on internal wave activity in LK (SAGGIO & IMBERGER 2001).

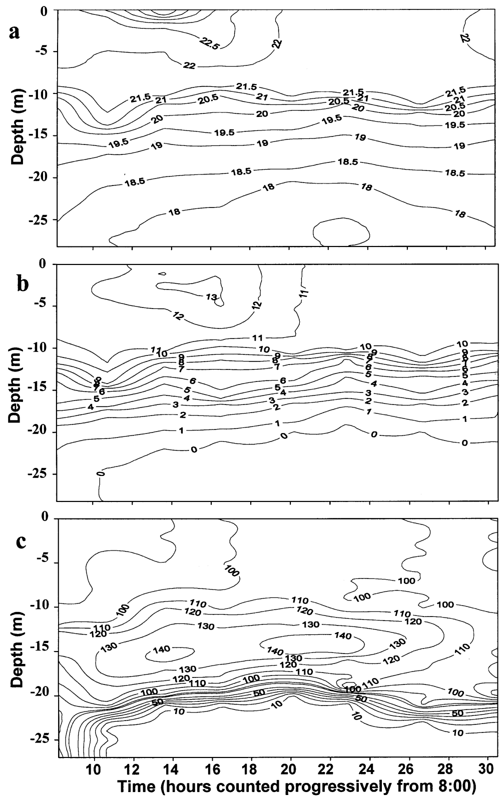

Fig. 1. Isopleth diagrams for (a) temperature (°C), (b) DO (ppm), and (c) nitrate (ppb) drawn from profiles measured at the 28-m station between April 29 and 30, 1999.

Algal patchiness could not be observed during this survey. The chl *a* content (not shown) in the upper 10 m of the water column was, on average, 25 µg L^{-1} with a constant phytoplankton assemblage consisting of green algae (40%), diatoms (30%) and dinoflagellates (30%).

The isotherm displacement diagram in Fig. 2a summarizes the thermal structure in the water column during the second survey (July 8–9, 1999). Similar to the first survey, the thickness of the epilimnion (T >28 °C) varied only slightly between 14 and 15 m. In contrast, that of the metalimnion (19–28 °C) fluctuated strongly from 8 m (9:00 h) to 5 m (18:30 h), expanding to 14 m by 24:00 h. This phenomenon, known as thermocline opening, was shown previously in relation to internal wave

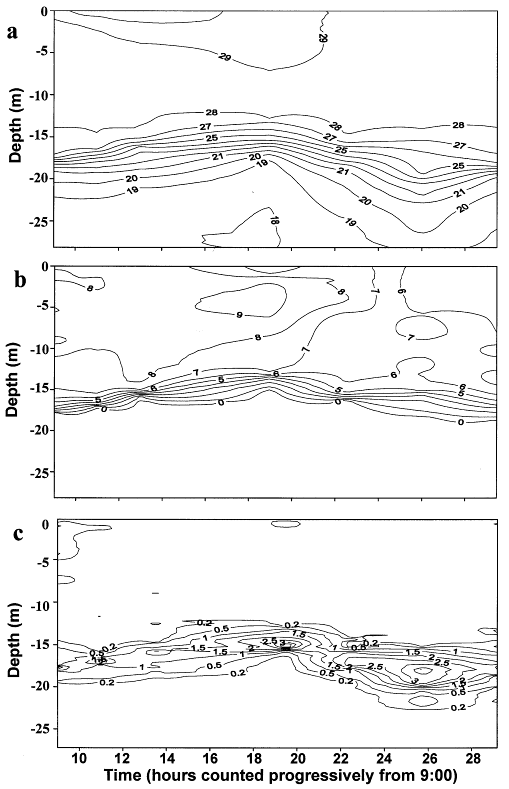

Fig. 2. Isopleth diagrams for (a) temperature (°C), (b) DO (ppm), and, (c) turbidity (NTU) drawn from profiles measured at the 28-m station between July 8 and 9, 1999.

activity in LK (ANTENUCCI et al. 2000). As a result, hypolimnetic water colder than 19 °C was pushed out of the experimental site by 24:00 h.

As indicated by the DO isopleth diagram (Fig. 2b), when compared with April, the position of the oxycline had changed to the upper part of the metalimnion following the 23 °C isotherm. Epilimnetic DO concentrations varied between 6 and 9 mg L^{-1}, showing a maximum at 19:30 h (5 m) and a minimum after 26 h (upper 5 m). Turbidity values measured in the epi- and hypolimnion were low (≤0.2 NTU; Fig. 2c). In contrast, metalimnetic turbidity values were at all times greater than 0.2, with peaks between 3 and 5 NTU, and, as such, presented an indicator for the thickness of this zone. As in the case of nitrate (Fig. 1c), the observed patchiness is probably a consequence of advection.

A pronounced time effect occurred with regard to the measured SRP profiles (Fig. 3). While epilimnetic SRP concentrations were generally low (<4 µg L^{-1}), those measured in the meta- and hypolimnion fluctuated between 4 and 35 µg L^{-1}. Each profile resulted in a differently shaped vertical SRP distribution, with the concentration in the near bottom zone being highest at 19:30 h and lowest at 01:45 h.

The diurnal variation of phytoplankton density and composition (not shown) was mostly low. The overall average chl *a* concentration in the depth range from 0 to 27 m was 7.8 µg L^{-1}. Chl *a* concentration showed a peak at a depth of 3 m, varying within a limited range in the upper 20 m of the water column, and then declining rapidly. Diatoms and dinoflagellates were the most important components of the phytoplankton, constituting 91–99% of the total.

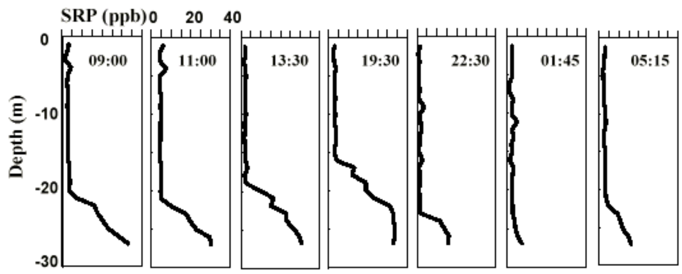

Fig. 3. Soluble reactive phosphorus profiles measured at the 28-m station between July 8 and 9, 1999.

In summary, the results showed a high variability in biogeochemical parameters in relation to changes in the physical structure of the metalimnion. The time and depth of sampling are critical for the results and their extrapolation during mass balance considerations. Previous research on the effect of physical forcing on the biogeochemical conditions in the water column had shown that chemical features are well trapped within the thermal structure of the lake (ECKERT et al. 2002). This implies that the high chemical variability found with the time change in the thermal structure should disappear once the data are plotted against temperature rather than depth. Figure 4 demonstrates that this hypothesis holds for the dataset measured during the second survey. The observed increase of SRP towards the lake bottom which, according to a comparison between Figs. 2a and 3, was obviously linked to the thickness of the hypolimnion, can now be identified as a stable P gradient within a water layer between the 18 and 21 °C isotherms (Fig. 4a). The same is true for turbidity data (Fig. 4b), leading to a nearly Gaussian distribution between the 19 and 28 °C isotherms. The most pronounced is the pH–temperature relationship (Fig. 4c), where all profiles fell into one line.

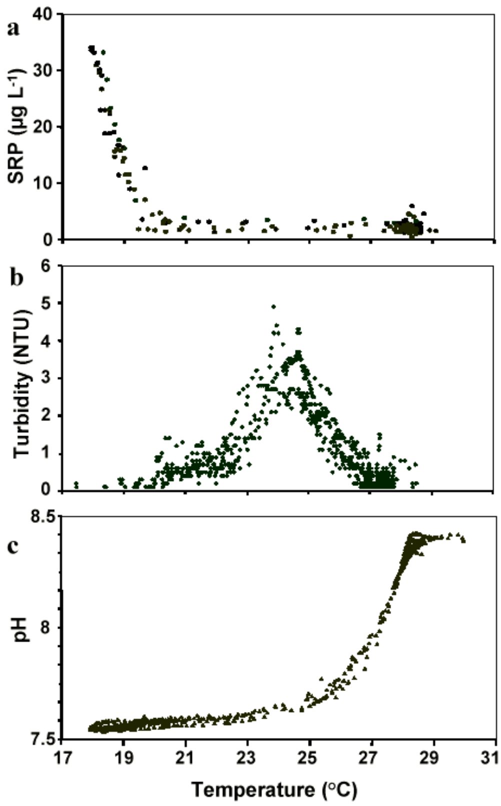

Fig. 4. Plot of (a) SRP, (b) turbidity, and (c) pH versus temperature from the datasets measured between July 8 and 9, 1999.

Conclusions

From the results of the present study the following conclusions can be drawn.

- During the period of stratification, chemical differentiation in the water column is strongly linked to the physical processes.
- Once thermal stratification is established, chemical features (SRP, pH) are embedded into the thermal structure of the lake.
- Short-term fluctuations in the chemical properties due to internal wave activity are governed by advection and become insignificant when related to temperature.
- Local patchiness, as observed in the cases of metalimnetic nitrate concentrations and turbidity, are a consequence of strong advective transport.
- Biologically relevant patterns may be better ascertained by dividing the vertical structure of the water column into temperature rather than depth zones.

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