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EXCHANGE PROCESSES BETWEEN LITTORAL AND PELAGIC WATERS IN A STRATIFIED LAKE

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Abstract. *The physical processes responsible for the exchange of water and particles between lake boundaries (littoral) and interior (pelagic) are investigated using field data and the three-dimensional hydrodynamic Estuary and Lake Computer Model (ELCOM) in Lake Kinneret, Israel. The field data revealed large-scale metalimnion oscillations with amplitudes up to 10 m in response to westerly diurnal winds and the existence of a well-defined suspended particle intrusion into the metalimnion of the lake. The changes in the thermal structure explained the observed vertical and horizontal movements of the suspended particle intrusion. The horizontal advective transport via the metalimnion, associated with the velocities induced by the basin-scale mode-two Poincaré wave, controlled the exchange between lake boundaries and interior on daily timescales. Detailed comparison of simulation results with field data revealed that the model captured the lake hydrodynamics for time scales from hours to days. The numerical simulation showed bottom shear velocities capable of resuspension and so a source of the observed suspended particle intrusion. Together, field data and numerical modelling clarified the flux path of water and particles between littoral and pelagic waters in the lake and demonstrated the importance of a proper characterization of the processes involved required for modelling and management of water quality resources.*

1 INTRODUCTION

Water motions in lakes primarily result from the combined forcings of wind stress, rotation of the Earth, density gradients and basin geometry. In freshwater lakes, the density field is mainly determined by the temperature distribution, which represents a balance among many processes, including air-water exchange, transport by currents and vertical turbulent mixing. The vertical thermal structure of a lake, which shall be referred to as stratification, is probably the most important physical/chemical/biological factor in determining water quality, controlling the vertical exchange of oxygen and nutrients and thus the biomass productivity of the lake ecosystem[1]. Energy imparted by the wind to a stratified lake leads to basin-scale internal waves, which distribute the energy throughout the lake over different time and length scales and provide an important link in the understanding of flux paths in stratified lakes[2,3,4].

It has been shown that the major portion of energy from basin-scale internal waves is dissipated by bottom interactions, and the minor portion is dissipated in the interior by shear instabilities or breaking of internal waves[3,5]. Laboratory experiments[6,7] and field observations[8,9] have revealed that the interaction of internal waves with topography is an important source of turbulence in sloping boundaries of lakes. This interaction contributes to sustaining the benthic boundary layer (BBL)[10,11,12], a region where mixing is enhanced compared to the inner part of the lakes[8,9].

Recent field studies have highlighted the importance of boundary mixing for sediment resuspension and nutrients supply in stratified lakes. They have also provided evidence that a one-dimensional (1D) approach of mixing in the metalimnion is insufficient for understanding the vertical flux of particles in stratified water bodies[8,9,13]. Instead, a two-dimensional (2D) approach is needed to describe the movements of particles where the vertical transport is mainly dominated by turbulence at the boundaries and advective processes or intrusions from mixing provide lateral transport of particles and solutes to the lake interior[14,15]. Thus, enhanced concentrations probably persist in a limited area for only a brief time before they are diluted or transported horizontally, depending on the magnitude of the horizontal current speeds and the lake size. The management of the quality of water resources depends crucially on an understanding of the relevant processes defining the flux path of particles and water within the lake system[3]. Little seems to be known about the processes controlling horizontal transport between lake boundaries (littoral) and interior (pelagic).

This study is an example for the possible extent to which numerical methods after proper validation and field measurements may be combined in order to gain a more coherent understanding of the behaviour of lake motions as a basis for understanding the lake ecosystem. Measurements of water temperature and wind velocities from five-on lake stations, one full meteorological station, and turbidity profiles in Lake Kinneret (Israel) were analysed in order to address the processes underlying the exchange between lake boundaries and interior, as well as the spatial and temporal scales on which these processes occur. Validated three-dimensional (3D) simulations were used to assist in the interpretation of the field measurements. A spatiotemporally distributed wind field, which included the wind curl and surface heat fluxes were used to force the numerical model. Investigated phenomena include basin-scale internal wave climate and the exchange processes between lake boundaries and interior. The terms lake boundaries and littoral, and lake interior and pelagic are used interchangeably.

2 METHODLOGY

2.1 Study Site

Lake Kinneret (The Biblical Sea of Galilee) is a warm, monomictic lake, located in the northern end of the Afro Syrian Rift Valley in northern Israel at about 209 m below mean sea level (Fig. 1). It plays a major role in Israel's water economy and currently supply about the 40 % of the nation's drinking water. The lake is pear shaped, with an east-west extent of 12 km and a north-south extend of 22 km. Maximum and mean depths are 43 and 24 m respectively. The water level changes annually due to imbalances in inflow and abstraction. From early May until late December, the water column exhibits a stable density stratification with a surface layer (epilimnion) depth of roughly 10 m, overlying slightly stratified bottom water (hypolimnion) that are separated by a zone of high temperature gradients (metalimnion). During summer afternoons, the lake experiences a strong, westerly, daily sea-breeze[16] (wind speed ~ 10 m s^{-1}). This intense forcing tilts the highly stratified metalimnion, resulting in basin-scale internal waves dominated by four components: a 24-h period vertical mode-one Kelvin wave, a 12-h period vertical mode-one Poincaré wave, and 20-h period vertical mode-two and -three Poincaré waves[16,17,18]. It has been found that the interactions between these waves and the sloping lakebed induce a turbulent BBL[12] which has a significant influence on the timing and site of the biogeochemical processes and may also serve as a catalyst for organic matter degradation, leading to enhanced accumulation of dissolved nutrients[19]. It has been suggested that suspended particles and nutrients are transported directly from the BBL into the metalimnion[2,20]. However, the processes responsible for such an exchange were not evaluated in these studies.

2.2 Field experiment

From day 165 through day 183 of the year 1999 (14 June-2 July) there were 5 thermistor chain moorings (labelled T1, T2, T3, T4 and T5 in Fig. 1) aligned with the principal axis of the dominant wind direction to document the horizontal structure of the basin-scale internal waves in response to the wind forcing. Each chain consisted of high-resolution (0.001 ^{o}C) temperature sensors, 12 for chain T1 and 20 for chains T2, T3, T4 and T5. The thermistors were placed at 1-m intervals in the metalimnion and at greater intervals in the epilimnion and hypolimnion. All stations were fitted with wind speed and wind direction sensors mounted 2.4 m above the water. Samples were collected at 10-s intervals. Meteorological data from Tabha (Fig. 1), a shore-based station, were recorded at 600-s intervals.

During different 24-h periods, vertical profiles of temperature, conductivity, pH, density and turbidity were measured using the Fine Scale Profiler (F-probe) in a grid of twenty-five stations on the western shallower regions, covering a sector that is one-quarter of the lake area

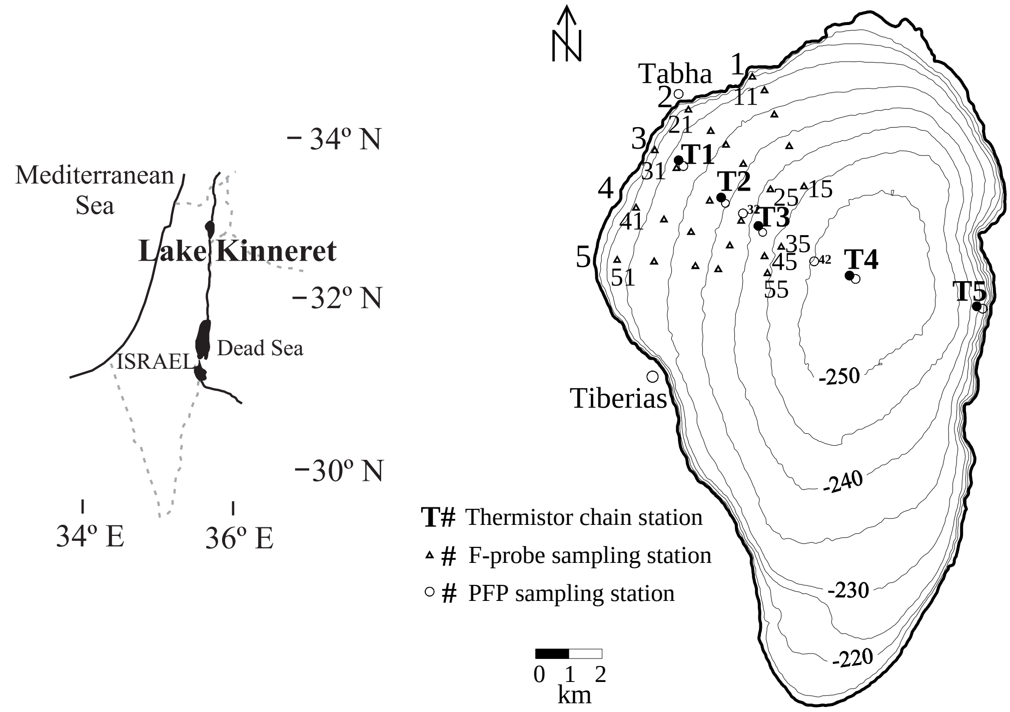

Figure 1: Lake Kinneret (32º50'N, 35º35'E) location and bathymetry showing the locations of relevant sampling stations during the 1999 field experiment. Depth contours are given in metres below the sea level.

(Fig. 1) to trace the horizontal and vertical evolution of the above variables in response to the basin-scale internal wave field. The normal profiling sequence began at Sta. 15 and proceed shoreward to Sta. 11 and then move to the following transects. A complete set of profiles from Stas. 11 to 55 was obtained in about 3.5 h, thus variations due to basin-scale internal wave motions can be neglected during that time.

Temperature and velocity microstructure profiles were recorded at various times and locations using a Portable Flux Profiler (PFP)[12]. In this work the velocity microstructure profiles are only used to compare with simulated velocities.

The position of each sampling site was recorded with a DGPS (Differential Global Positioning System). To ensure accuracy and correct performance, all instruments were calibrated before and after sampling. For the purposes of this study, analysis is focused on data collected between days 171 and 182 because this time period is coincident with the largest data availability.

2.3 Numerical simulations

Simulations were performed with the Centre for Water Research (CWR) Estuary and Lake Computer Model (ELCOM), which has previously been successfully applied to model the hydrodynamics of stratified lakes, including Lake Kinneret[21,22,23,24]. The code solves the 3D Navier-Stockes and scalar transport equations separating mixing of scalars and momentum from advection and making use of the hydrostatic and Boussinesq assumptions[21]. The model includes a filtering technique to control the cumulative effects of numerical diffusion of potential energy[22] and a new 3D mixing layer model[23]. Stress at the surface boundary due to wind was modelled as a momentum source distributed vertically over the surface wind mixed layer[21]. The bottom shear velocity was calculated as

$$u_*^2 = C_{Dbott}\ u_{bott}^2 \tag{1}$$

where u_{bott} is the magnitude of the instantaneous horizontal velocity in computational cells adjacent to the bottom and C_{Dbott} is the bottom drag coefficient taken to be 3×10^{-3}, appropriate for a mud/sand bottom[25].

Simulations were conducted with a model bathymetry having a maximum water depth of 41.2 m, 400 m horizontal grid size, and 1 m vertical grid size. No-slip boundary conditions were used for horizontal bottom boundaries and free-slip boundary conditions were used for vertical land-boundaries. The model was initialized with a horizontally uniform temperature profile, a horizontal free surface, and zero velocity everywhere. The simulated period covers days 171.5-181.5 with a time step of 300 s.

The simulation was driven with meteorological data excluding wind (air temperature, relative humidity, and incoming short wave radiation) collected at Tabha Station (Fig. 1). A cloud cover fraction of 0.20 was assumed for the period of simulation. The wind field over the lake surface was constructed from the measured wind at Sta. T3 combined with the calculated north-south component of the wind curl time series to arrive at a surface wind at each grid point of ELCOM (i.e. 400-m grid) at each simulation time step[26]. Simulation spin-up time for the basin-scale internal waves was about 24 h; the period of the vertical mode-one internal Kelvin wave[21].

3 FIELD RESULTS

3.1 Meteorological forcing

During the analysis period the weather was warm with calm mornings and windy afternoons (Fig. 2). The air temperature varied between night and day and somewhat between days, ranging from about 23 ºC to 35 ºC (Fig. 2a). Maximum air temperatures were several degrees warmer on days 173 and 180, and minimum air temperatures were lowest on day 176. The wind pattern was dominated by a strong diurnal cycle with calm mornings and strong westerly winds, which commenced in the early afternoon and lasted for 6 to 8 h (Fig. 2b,c). Speeds over 8 m s^{-1} occurred daily; a maximum wind speed of over 12 m s^{-1} occurred on days 171 and 173.

3.2 Temperature structure and basin-scale internal wave field

As shown in Fig. 3, the water column was strongly stratified over the study period, with epilimnion temperatures between 27 and 28 ºC and a hypolimnion temperature of about 16 ºC, and a sharp metalimnion at around 17 m. The surface layer temperature in the eastern shore was consistently 2 ºC higher than that in the center and western shore of the lake.

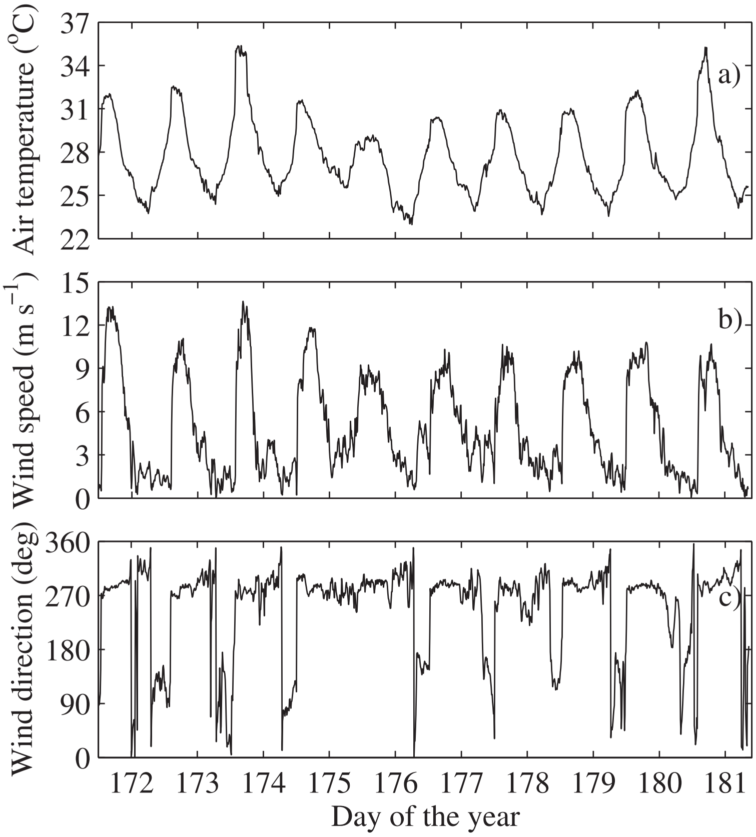

Figure 2: Records of the: a) 1-h average of air temperature at Tabha Station, b) 10-min averages of wind speed and c) wind direction (meteorological convention) recorded at Sta. T3.

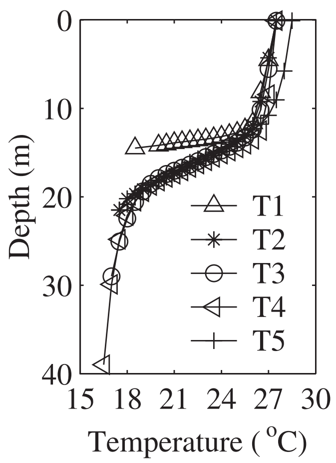

Figure 3: Vertical temperature profiles derived from the thermistor chain data and calculated as the average depth of the isotherms over the analysis period.

The isotherm displacements also showed a daily pattern and revealed the existence of large-scale metalimnion oscillations with two main forms dominating (Fig. 4a-e). The first correspond to a 24 h vertical mode-one Kelvin wave[17] while the second a 12-h vertical mode-one Poincaré wave[18]. The opening of the metalimnion at Stas. T2 and T5 (Fig. 4b,e) was identified as the result of mode-two and -three Poincaré waves[18] with a period of about 20 h. Visual inspection of the temperature records (Fig. 4) shows that the amplitude of the 24-h periodicity associated with the mode-one Kelvin wave decayed towards the lake centre; the 24 h peak at Sta. T4, near the lake centre, was smaller than at the other stations (Fig. 4d). These observations are confirmed by the spectral analysis (Fig. 5) that indicates that the basin-scale internal wave field during the 1999 field experiment was similar to that observed previously[12,18,23].

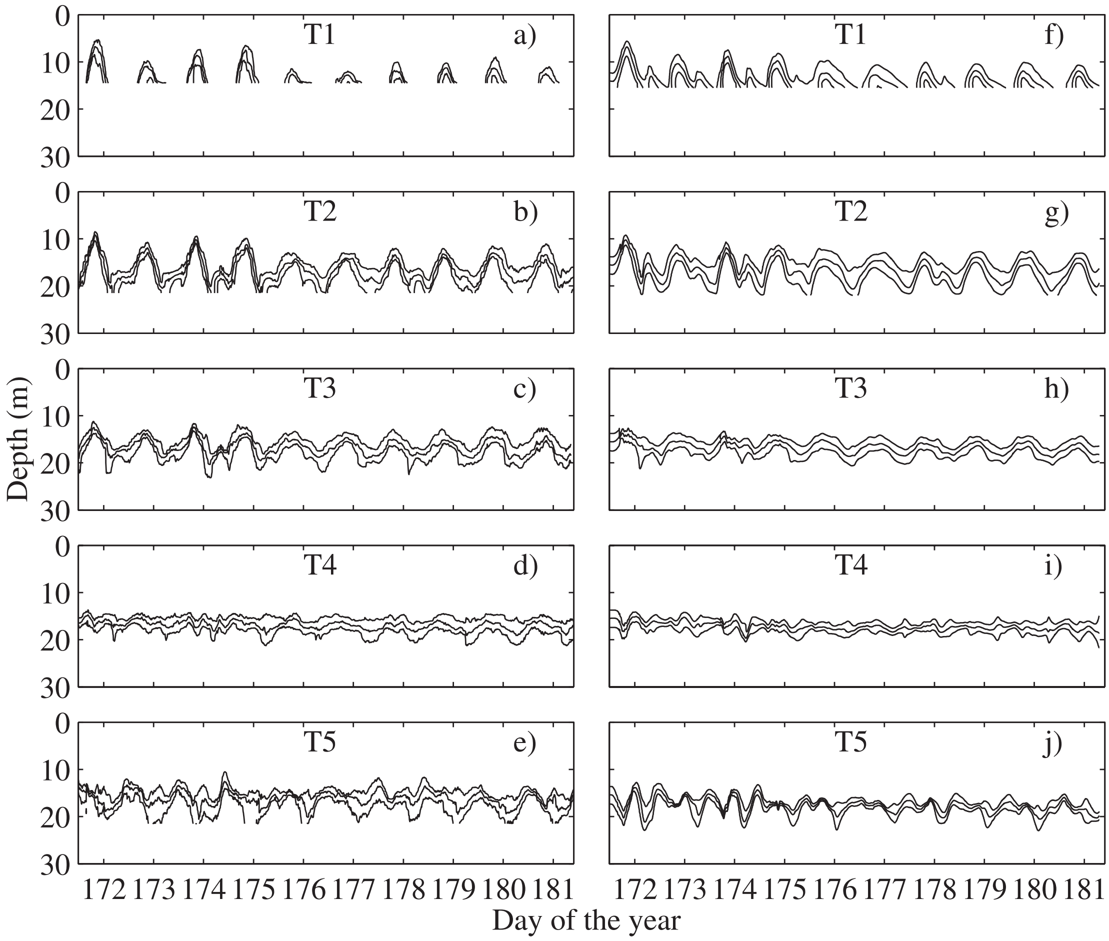

Figure 4: Isotherm displacement during the analysis period. (a-e) 20-min averages of field data; (f-j) 300-s interval model results. Isotherm heights were calculated through linear interpolation. In each panel, the bottom isotherm is 20 ºC and the contour interval is 2 ºC.

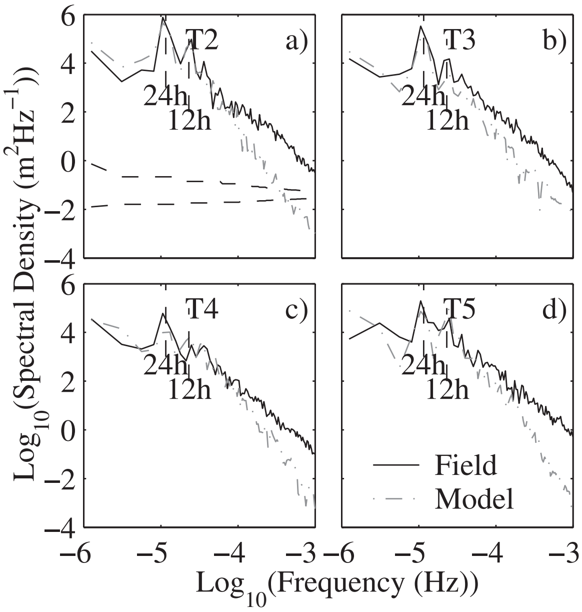

Figure 5: Power spectra of the 22 ºC isotherm displacement from field data (solid lines) and model simulation (dash-dotted lines) at Stas. a) T2, b) T3, c) T4, and d) T5. The 95 % confidence interval for all panels is given as the vertical distance between the two dashed lines in panel a). Frequency corresponding to 12 and 24 h indicated as dashed vertical lines in all panels.

3.3 Temperature and turbidity transects

Short-term changes in temperature and turbidity in the water column caused by the action of the basin-scale internal waves were observed in the northwestern quarter of the lake. Data collected between 11:02 h on day 178 and 01:46 h on day 179 along transect 21-25 (Fig. 1) were analysed in detail (Fig. 6). These data cover periods before, during, and after the maximum wind strength and are typical of most day observations during the field experiment.

The thermocline rose from 18 m depth at 11:00 h (Fig. 6a) to 12 m at 16:00 h (Fig. 6b) as the Kelvin wave upswing passed through the stations (see Fig. 4a-c) then dropped to 18 m at 21:00 h (Fig. 6c) and to 20 m by 01:00 h (Fig. 6d). A well-defined turbidity layer with elevated concentrations in the metalimnion was confined between the 20 and 26ºC isotherms, transported vertically through the water column by vertical advection (Fig. 6a,b). Note that the turbidity layer, while being vertically advected, was situated between 12 and 16 m depth. The turbidity layer changed thickness with time at Stas. 22, 23 and 25 (Fig. 6c,d). Vertical profiles of velocities showed an intrusion current, or a metalimnetic jet, between 7 and 14 m (Fig. 8), 9 h after the onset of the wind, with peak speeds of 0.20 m s^{-1}. Such jets are typical for Lake Kinneret and were identified as the mode-two Poincaré wave[18] dominating the velocity structure during the evening hours. The changes observed in the turbidity suggest that the water in the metalimnion is being advected horizontally by these mode-two motions towards the lake interior. Of particular interest is the presence of elevated turbidity concentrations near the bottom (Fig. 6c,d) at the time of the thermocline downdraft.

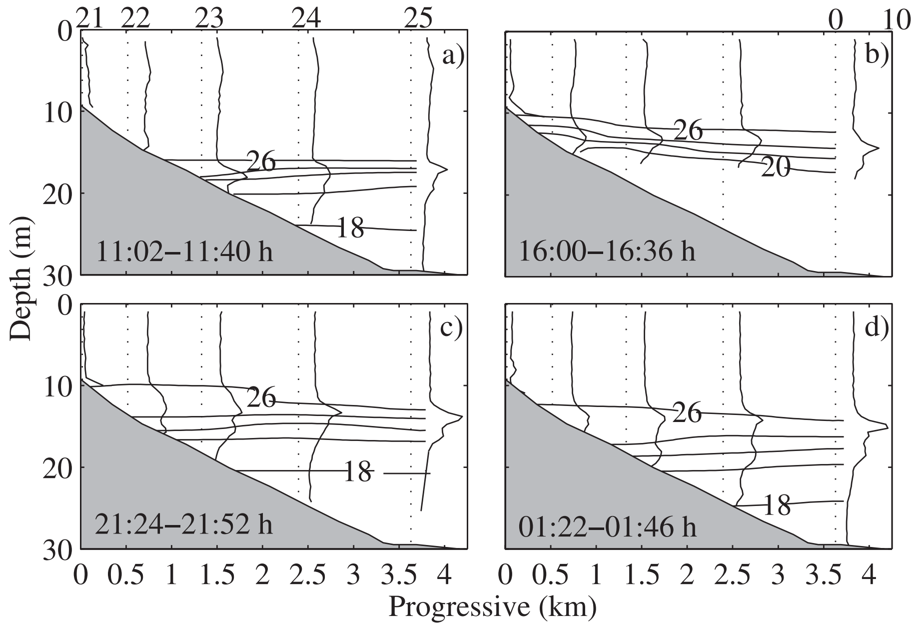

Figure 6: Temperature contours derived from the F-probe profiles measured along the transect 21-25 between days 178 and 179 at a) 11:02-11:40 h, b) 16:00-16:36 h, c) 21:24-21:52 h and d) 01:22-01:46 h. Turbidity profiles for the same time interval are superimposed and shown as heavy lines with the axis originating at the location where the profile was obtained. Turbidity readings are expressed as Formazin Turbidity Units (FTU). The zero on the x-axis is the location of Sta. 21 shown in Fig. 1. Location of the F-probe profiles is indicated as thin dotted vertical lines. The bottom isotherm is 18 ºC and the contour interval is 2 ºC.

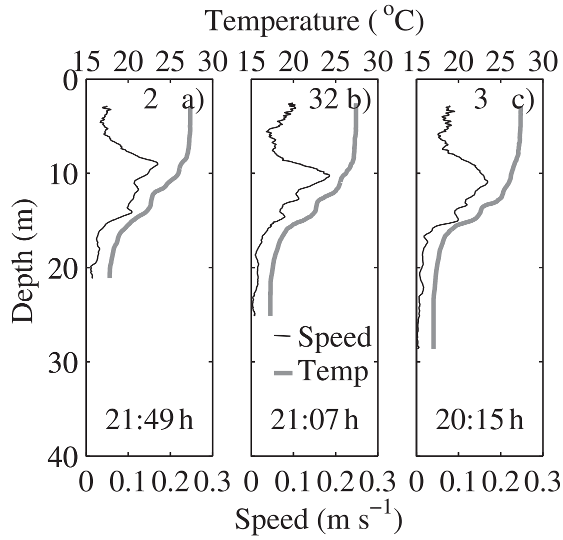

Figure 7: Vertical profiles of speed and temperature recorded at Stas. a) 2, b) 3 and c) 32. Profiles were collected with the PFP on day 180. Multiple profiles at each station were smoothed over 5 cm and averaged together.

It is interesting to note that the turbidity layer thinned as the thermocline moved upwards and thickened as the thermocline moved downward. At all stations the turbidity layer tended to return to the condition observed before the onset of the wind. This pattern was consistently repeated each day.

Depth-averaged turbidity contours between 12 and 17 m show that turbidity concentrations vary spatially during the day, and maximum concentrations were observed towards the northwestern shore and decreased towards to the centre of the lake (Fig. 8). Peak turbidity concentrations were observed just after the crest of the vertical mode-one Kelvin wave passed the profile location (see Fig. 4a-c).

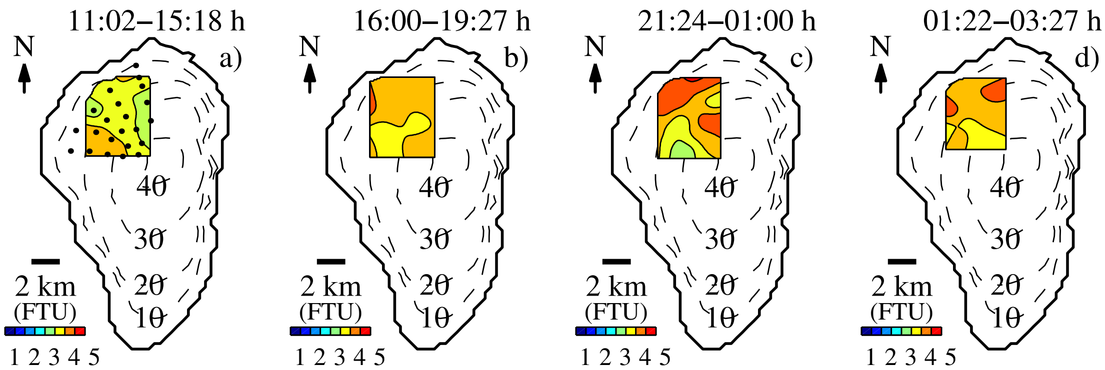

Figure 8: Snapshots of depth-averaged turbidity contours between 12 and 17 m depth obtained from a complete set of spatially interpolated profiles (from Stas. 11 to 55) at four different times between days 178 and 179. Dots indicate the locations of the sampling stations.

4 MODEL RESULTS

The comparison of simulated (Fig. 4f-j) and field results (Fig. 4a-e) shows that the model captures the phases and amplitudes of the basin-scale internal wave field quantitatively well. The spectra from the model results are also shown in Fig. 5 (dash-dotted lines), which shows that ELCOM successfully reproduced the vertical mode-one Kelvin and Poincaré waves energies and frequencies, and the measured and simulated spectra are well matched up to about 7×10^{-5} Hz (4 h). This result is similar to that already noted in Lake Kinneret previous simulations[21,23]. The model also provided good estimates of the velocity structure in the water column, arising from the dominant basin-scale internal waves (Fig. 9). In particular, the feature between 10 and 15 m due to higher vertical mode Poincaré wave[18] is well captured by the model.

5 DISCUSSION AND CONCLUSIONS

The goal of the present study was to identify the processes underlying the exchange between lake boundaries and interior in a stratified lake. The modelling approach, used in conjunction with field observations, provides a powerful tool for studying the spatial and temporal structure in lake hydrodynamic processes.

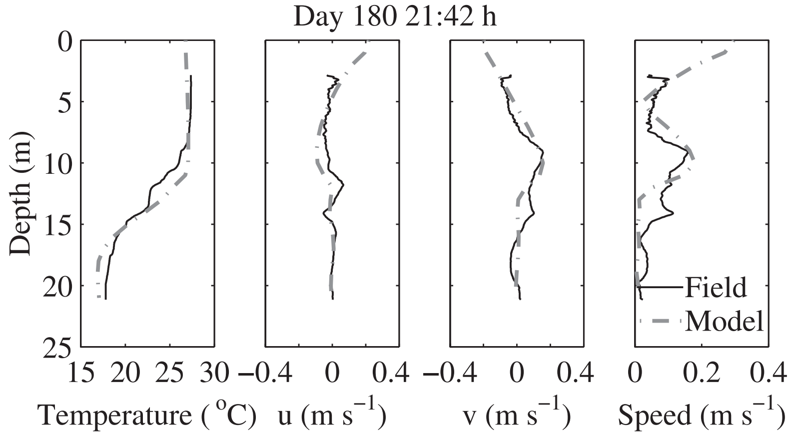

Figure 9: Comparison of observed and simulated vertical temperature and velocity profiles. Field data are from several PFP profiles collected at Sta. T2 and averaged together. Simulated data were linearly interpolated to the time and depth of field data measurements.

Taken together, the diurnal cycle of heating and strong westerly winds produce a setup of the metalimnion, and subsequent internal wave motions. The observed evolution of the internal wave climate documented in 1999 was comparable to previous studies[12,18,23]. Periods, amplitudes, and phases of the dominant internal waves were simulated well with a wind field, which included the wind curl. The numerical results showed dramatic improvements over previous modelling results, which used uniform wind and spatially varying wind fields[21,23] for both the simulated wave amplitudes and phases at all stations. In these previous studies, no comparison of velocity records was made. In Fig. 9, the measured velocity profiles plotted against the numerical results illustrates the good level of agreement attained in the simulation. The fact that in different locations of Lake Kinneret the observations of temperature fluctuations, velocity and previously reported drogue tracks compared reasonably well with the simulations results, offered confidence in the validity of the results.

F-probe profiling during different 24-h periods indicates the existence of a well-defined turbidity intrusion near the northwestern shore into the metalimnion, being heaved up and down by the vertical mode-one Kelvin wave. One likely source of the observed turbidity layer is particle resuspension. Sediments in the northern and western part of the lake are richer in fine-grained detrital material (2-20μm) because the main input is from the Jordan River [27] and certainly constitutes a readily available particle source to the turbidity layer. It has been suggested that resuspension of bottom material occurred where metalimnetic isotherms intersect the bottom area[20,28] (between 15 and 19 m depth). The turbidity measurements showed an increase in near bottom turbidity concentrations (Fig. 6c,d), during the period of the thermocline downdraft. The numerical simulation showed bottom shear velocities higher than the threshold value for Lake Kinneret unconsolidated silty and sandy sediments[29] and so capable of resuspension in that area at the times of the thermocline downdraft (Fig. 10). Near-bottom currents of up to 0.18 m s^{-1} resulted from the model[26] and compared well to reported values of previous studies[30] at the depth of 21m on the northwestern shore during the night times. Resuspension is then associated with these instantaneous bottom currents ranging up to

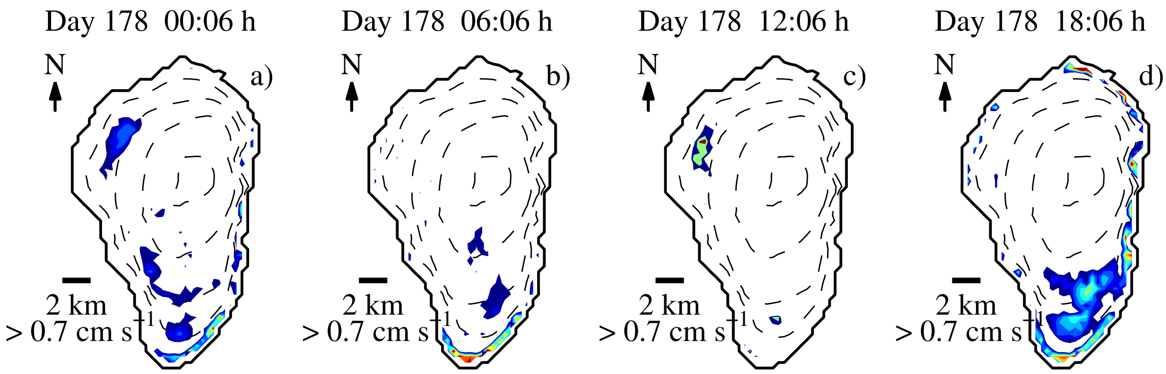

Figure 10: Snapshots of the bottom shear velocities computed using simulated velocities 1 m above the lakebed at four different times during day 178. Only the regions where friction velocities exceed 0.7 cm s^{-1} are shown.

0.18 m s^{-1} during the thermocline downdraft. It is also interesting to note the spatial variability in the bottom friction velocities, which will result in localized resuspension of sediments from the bottom back into the water column. Using organic matter and pigments as tracers, an essential decrease in the proportion of resuspended material in bottom sediments from the peripheral zone of the hypolimnion toward the lake interior was found[20]. Since the resuspended particles are subject to resettling by gravity when the shear stress diminishes, this process of resuspension may take place repeatedly, and the particles may be recycled several times at the same place or eventually transported by currents to the lake interior or to the epilimnion by upward currents associated with the rising thermocline.

In Lake Kinneret, it has been suggested that the particles, once resuspended, may be transported horizontally toward the lake centre by fast-moving metalimnetic jets as shown in Fig. 2.6, pumping the mixed inshore waters towards the lake interior[20]. The turbidity observations confirm this hypothesis. As a first approximation, the time for a resuspended particle to travel from Sta. 22 to 25 can be estimated in Fig. 7. The distance between both stations is about 3000 m and the velocity in the upper metalimnion was about 0.15 m s^{-1} (Fig. 7). Consequently, the estimated time would be approximately 5 hours. An increase and redistribution of the turbidity concentrations during that time, from its source towards the lake interior, is indeed observed in Fig. 8c,d. It is then suggested that the horizontal advection in the metalimnion by the mode-two Poincaré motions can explain the observed horizontal variations in the turbidity concentrations, observed over both time and space. Horizontal current speeds and lake size determine whether the particles remain in the littoral zone or are swept offshore. The results from the turbidity data provide evidence that the exchange between lake boundaries and interior is controlled by horizontal transport via the metalimnion on daily timescales.

It can be concluded that the near shore hydrodynamics are of fundamental importance when considering the cycling of sediment throughout the lake. The ecological impact of the near shore water exchange has the potential to be severe in terms of higher turbidity, nutrients enrichment and toxicity.

6 ACKNOWLEDGMENTS

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