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Turbid intrusion below the thermal staircase in the seasonal thermocline of Lake Biwa

Kenji OKUBO*, Hiroshi MORIKAWA**, Takashi KIMOTO***, Yuji TANAKA****

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Thermal 'staircase', a layer of constant temperature between the sheets of the steep gradients, was formed in the seasonal thermocline, which was 2.5 m above the bottom at a point of 18 m deep on the boundary slope in Lake Biwa. Following a sediment resuspension event when a moderate onshore wind blew, bed materials should be suspended up to the thermocline, then settled down forming a staircase above the turbid intrusion. Comparing the observed downward heat flux with the settling flux of sediment, it was found that double-diffusive convection would play an important role on the formation of the whole structure consisting of the staircase and turbid intrusion along with chemical anomalies and dense population of phytoplankters, which were fed by nutrients supplied from the bottom sediment under a typical condition of drought. Laboratory experiments were conducted to demonstrate the thermal and sediment processes in the stratified lake. Resuspension process due to surface and internal waves was examined using a tank with a sloping bottom, while the settling process was investigated by using a deep, diffusive tank. Formative process and scales of the staircase and intrusion were discussed relating with the intensity of resuspension and the buoyancy fluxes.

1. INTRODUCTION

Physical processes in lakes differ from year to year depending on the meteorological conditions. In 1994, we suffered from a severe drought in Japan, while transparency of surface water in the deeper north basin of Lake Biwa was recovered considerably in the summer, and biologists noticed unusual vertical distribution pattern of plankters near the seasonal thermocline. As all the rivers ceased to flow into the lake for those several weeks until the rainfall on September 16, the major source of nutrients for biological production was the bottom sediments. In this situation, physical process across the sediment-water interface might have significant effects on biochemical aspects of the lake. Such interfacial processes as dissolution and resuspension from the bottom materials are evenly important as those in the air-water exchange in view of the buoyancy and other chemical fluxes.

Bottom sediments originally came from rivers forming turbid plumes after every considerable floods. Usually sediment resuspension would take place due to surface waves in the breaker zone under the homogeneous, well-

* Department of Environmental and Civil Engineering, Faculty of Environmental Science and Technology
** Graduate Student, Department of Civil Engineering, Faculty of Engineering, Kyoto University
*** Research Institute of OceanoChemistry, c/o Faculty of Science, Kyoto University
**** Department of Fisheries, Faculty of Agriculture, Kinki University

mixed water, which suspends even coarser sediment near shore. In deeper part, along the perimeter of seasonal thermocline, boundary mixing causes resuspension, in which any equilibrium profile of sediment concentration is hardly attained because the process is essentially transient. After resuspension events, bottom currents along the bed would be driven by the negative buoyancy due to lower temperature and/or higher sediment concentration, and most of those are submerged flows under homogeneous ambiance. When the lake is thermally stratified, the current detaches from the floor at a certain depth and the intrusion develops penetrating into the intermediate layer of particular density around the thermocline, depending on thermal conditions of the lake and its rivers. In spite of mechanism of resuspension, freshly suspended sediments tend to establish intrusions and fine sediments are advected by the density currents toward final sedimentation in the deepest area of the lake.

As those intrusions are so continual in Lake Biwa that indistinct 'staircase' structures in vertical temperature profiles have been noticed in deeper part of the lake, while no explanation has been made for these fine structures. Unstable temperature inversions of about half a degree are in fact seen in the profiles, so it is likely that density fields of lakes are generally due to two or more components of scalars which change local density of water, and thermal stratification in the freshwater lake is continuously adjusted by those minor density variations of turbidity mostly due to difference in silt particle concentration. Multiple component stratification is thus frequently found in freshwater basins, but the double-diffusive convections in such basins have not been proved so far. It is shown here that the similar structure to oceanic staircase below the permanent thermocline was seen in a relatively shallow depth range of the freshwater lake through the double-diffusive convective mechanism. Turbid intrusion conveys not only suspended sediments but also dissolved and other particulate matters, so sharpened peak or trough in the profiles of biochemical tracers are found around the intrusion. Such chemical anomalies or extremes strongly interact with biological processes of production, grazing and pumping being affected by the physical process to form the intrusion.

2. THE FIELD EXPERIMENT

From September 12 to 15 in 1994, collaborative field measurements were conducted in the southern part of the north basin of Lake Biwa shown in Fig. 1, where physical and biochemical surveys were carried out sharing data and samples. The area and the month of 1993 were much affected by turbid intrusions due to river floods influenced by typhoons. While in 1994, the thermocline was turbid only along its boundary edge where the hypolimnion was relatively thin and both the surface and internal waves tapped the lake floor. The thermocline was set rising up southward due to the internal seiching on September 13 and 15, and a resuspension event was seen on the former day.

In the afternoon of September 13, the thermocline was about 15 m deep and so sharp with the temperature gradient of about 10°C/m, which was not monotonous but with a mid layer of weaker gradient as found in Fig. 2(a). The temperature profiles were measured by using a 4 m long, 0.1m interval thermistors chain at a point, 18 m deep, north to the station D, close to CD, and near bottom turbidity was probed together with temperature variation in the

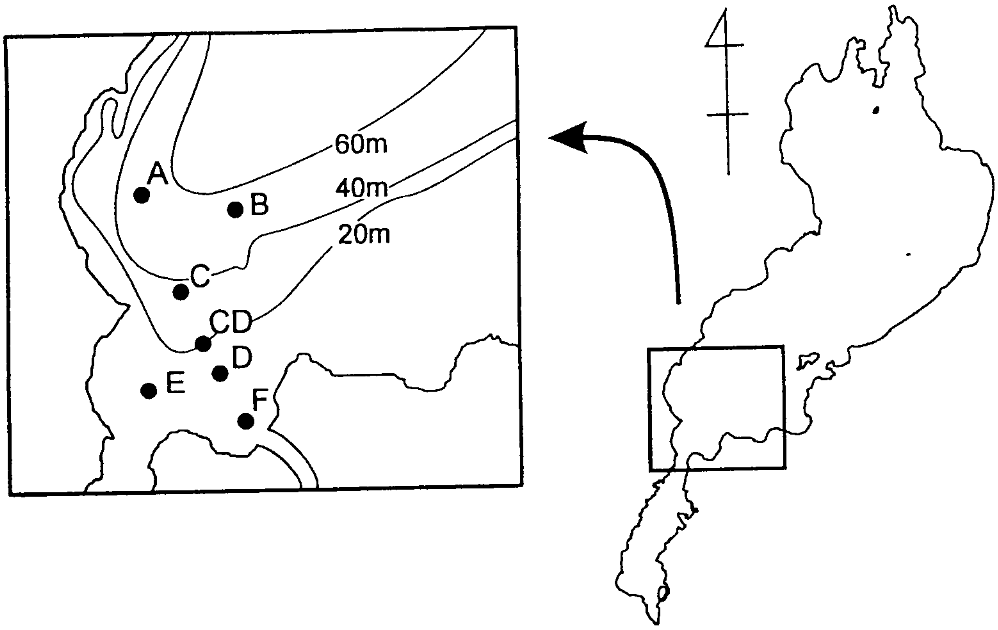


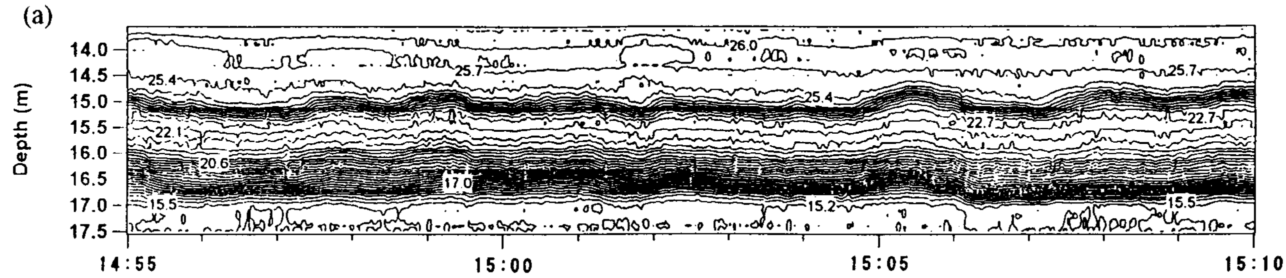
Fig. 1 Map of the area where the collaborative measurements in 1994 were conducted in Lake Biwa

benthic boundary layer. The thermocline was going to be changed into the thermal staircase as shown in Fig. 2(b). It was identical to the thermohaline staircase observed at a few hundred meters depth in the ocean (Mormorino et al., 1987), though the thickness was ten times larger and temperature differences between the successive layers were 1°C or less in the ocean.

After the former measurement of Fig. 2(a), a moderate northeast wind blew for several minutes, and we found turbidity variation enhanced in the monitor of FFT analyzer (R9211A/E, Advantest) connected to the turbidity meter (MA212D, Hokuto Riken) at 0.5 m above the bottom, with which the bottommost thermistor in the chain was fixed. Figure 3(a) is the early resuspension showing turbidity fluctuation of the burst, noticed at the local time 15:15, and the successive bursts are shown in Fig. 3(b), where the frequency components of wide range are noticed. The linear trend of turbidity variation was removed from the record and only fluctuation was shown. The shortest period was around 5 seconds and was close to those of surface waves. The intermittence was due to the longest period around 3 minutes and it is four times the minimum buoyancy period of 45 seconds, corresponding to the maximum buoyancy frequency, $N=[-(g/\rho_o)(d\rho/dz)_{max}]^{1/2}$, where g is the gravity acceleration; ρ_o and ρ: reference and local density of water; z: vertical distance taken positive upward.

The research vessel, Hakken from Lake Biwa Research Institute, moved from a station to another in turn, where we conducted daily casting of profilers and sampling of waters. According to turbidity profiles taken by an optical IR backscatterrance meter (OBS), an intrusion beneath the thermocline at the depth range of 15 to 17 m, was consistently found at all the deeper stations during those four days, and the peak turbidity of the intrusion was found to be 10 mg/l. On the shallower stations like D, E and F (Fig. 1), other intrusions of lower concentration were occasionally found around 10 m depth. Those minor intrusions above the seasonal thermocline sometimes extended to the deeper stations like CD and C within the day, but usually disappeared on the next day.

(a)



(b)

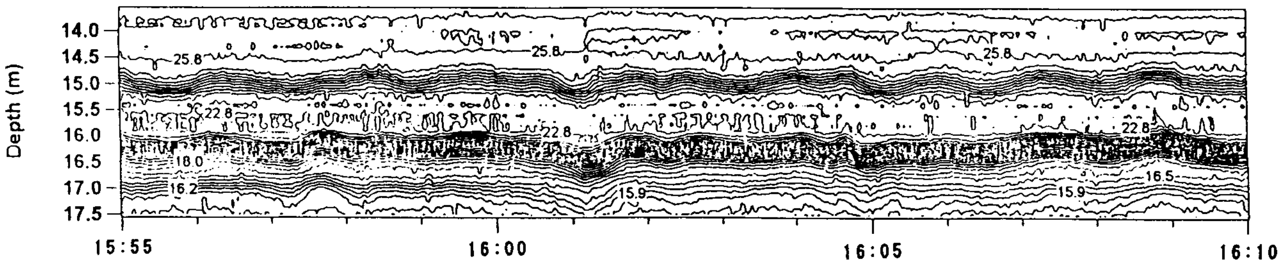
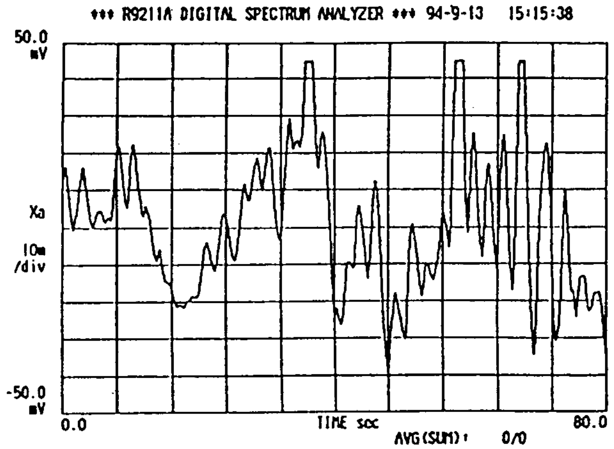


Fig. 2 Thermal structures (a) before and (b) after the sediment resuspension on September 13, 1994.

(a)



(b)

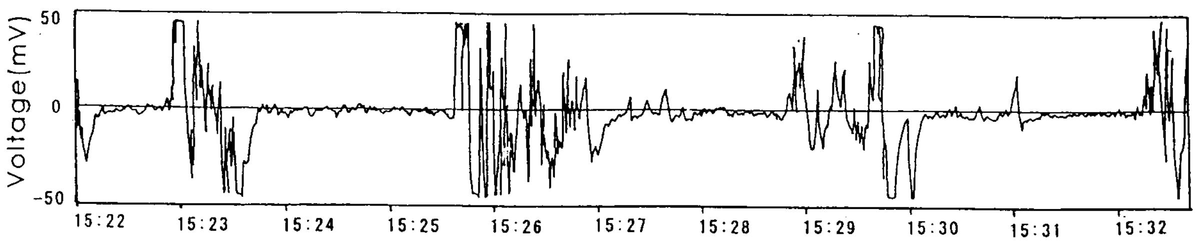


Fig. 3 (a) Turbidity fluctuation in which increasing or decreasing trend was removed. It is an early stage of resuspension and (b) Turbidity fluctuation during the resuspension.

Figure 4 shows the physical and biochemical profiles averaged for all the stations during the field experiments. In case of Lake Biwa of 1994, the major intrusion depth was according with the layer of the maximums in pH, dissolved oxygen (DO), fluorescence intensity (FL), and some of carbon cycle tracers. Particulate metals and plankters also showed their maximum concentrations at the depth of intrusion. Turbidity peak of the intrusion in the beam attenuation profile (BAT; m^{-1}) taken by the beam transmissiometer (Sea-Tech) on the profiler (Sea-Bird Electronics Sealogger; SBE) was found at 16 m depth, but the minor intrusions detected by OBS were smoothed out from the BAT profile.

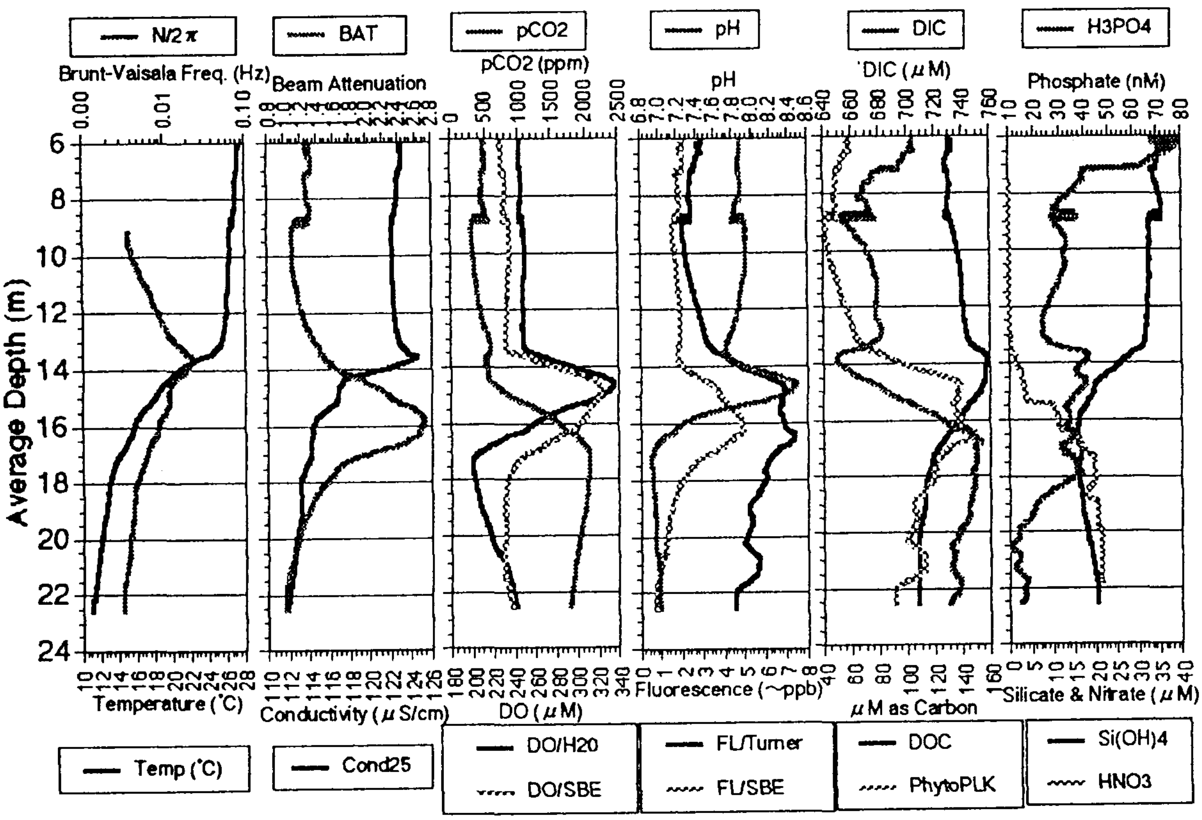


Fig. 4 Thoroughly averaged profiles from the profiler casting and water sampling during the collaborative field measurements in Lake Biwa from September 12 to 15, 1994.

Daily profilers casting at the stations revealed the stationary intrusion covered the measurement area, but it was not frequent enough to assess the highly transient profiles. Turbidity peak of intrusion was 10 mg/l after a cross calibration between OBS and BAT, while instantaneous maximum turbidity observed during the resuspension event in Fig. 3 was around 90 mg/l, so the average turbidity at 0.5 m above the bottom was 4 to 5 times higher than the peak turbidity. Such sediment cloud would be dispersed quickly but there is no direct evidence about the height to which the bed materials were suspended up beyond the intrusion.

Concentration peak of turbid intrusion divides the thermocline into two parts. The region below the peak is regarded as a finger regime and the respective thermal and sediment gradients are stable and unstable, which is a condition of double-diffusive convection (reviewed by Turner; 1973), provided that the region is molecularly quiescent. The region above the peak is simply stable because both the gradients are so, but its 'overstable' tendency would possibly bring another instability especially for disturbances of higher frequency because of the increased buoyancy frequency of the system. Therefore the structure around a single intrusion generally consists of the overstable and the finger regimes. Moreover, on September 13, there might be another intrusion above the thermocline within which the major intrusion was, and it was between the turbidity peaks where the staircase was formed. The sediment gradient in the staircase would be stable because the lower intrusion was with the higher concentration, while the temperature gradient in the staircase was weakly or neutrally stable, so it was rather close to the diffusive regime, although it should contain a locally inverted temperature profile and stabilizing factor should be free from settling, strictly speaking. Laboratory verifications were required to clarify the total process consisting of the resuspension and the settling phases.

3. FORMATIVE PROCESS OF TURBID INTRUSION

Laboratory experiments on sediment resuspension and resultant turbid intrusion were done by using a 4 m long, 0.1 m wide, 0.25 m deep, plastic made tank. A rigid plastic wedge was placed on a side of the tank, which formed an inclined part of the bottom, and angle of the slope was fixed. On the other end of the tank, there attached a wave generator designed so as to combine the effects of surface and internal waves. The apparatus is schematically shown in Fig. 5 with the arrangement of temperature, velocity and turbidity sensors and further details would be described in Morikawa et al.(1996). Here it will be shown some earlier results of the experiments to discuss the formative mechanism and process of intrusions.

First, quiescent two-layered fluid system was set up, then the wave generator was driven with the prescribed control mode. The amplitude and period ranges were 2 to 4 cm and 2.5 to 8.6 seconds, respectively. Temperature difference between the layers was 20°C ($\Delta\rho/\rho=0.004$), which kept the reduced gravity of 4 cm/s^2 and period of the basic internal wave of about 8 sec. On the sloping part of the bed, kaolinite clay dispersed in water, 140 % of the clay in weight, was placed with a thickness of 3 mm. After trials, it was found that pure internal wave did not make the clay suspended much, so we drove the surface waves with the generating paddle moving up and down

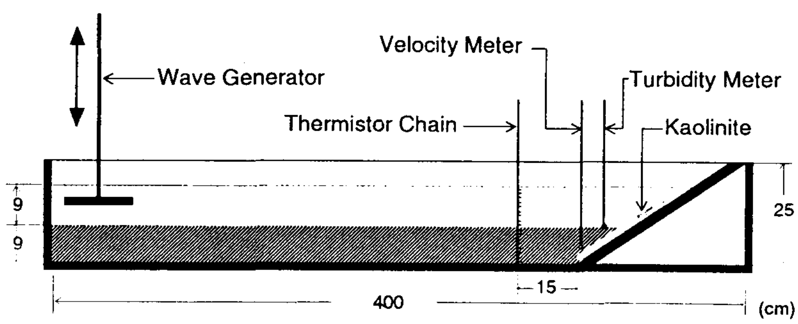


Fig. 5 Experimental setup of a two-layered fluid system in the tank with a partial slope.

within the epilimnion and internal waves of the buoyancy frequency were excited through the resonance mechanism. It seemed the same manner through which the resuspension was enhanced in the field. Moreover, internal seiches in the tank were ten times or more longer than the internal waves on the thermocline. The broader the resonance range between the surface and the internal waves, the higher resuspension was observed under the composite waves condition, where sediment was loosen by the surface wave with a period of several seconds and then entrained into fluids mainly by the internal wave motion, which was clear in velocity records above the slope, and fluctuated migration of the intrusive front. Elapsed time for an experiment was about 4 minutes, during which the thermocline was thickened from the generator side in the latter half of the experiment. As only the resuspension was interested in, so the wave generator was not turned off during the test. Figure 6 shows a relative concentration pattern of the experiment, B9 with the wave period of 2.7 seconds. An intrusion, 10 cm above the bottom, was obviously in the upper thermocline, below which, a weaker turbidity peak, 6 cm above the bottom, was also noticed under an initiated fingering of the lower surface of the upper intrusion.

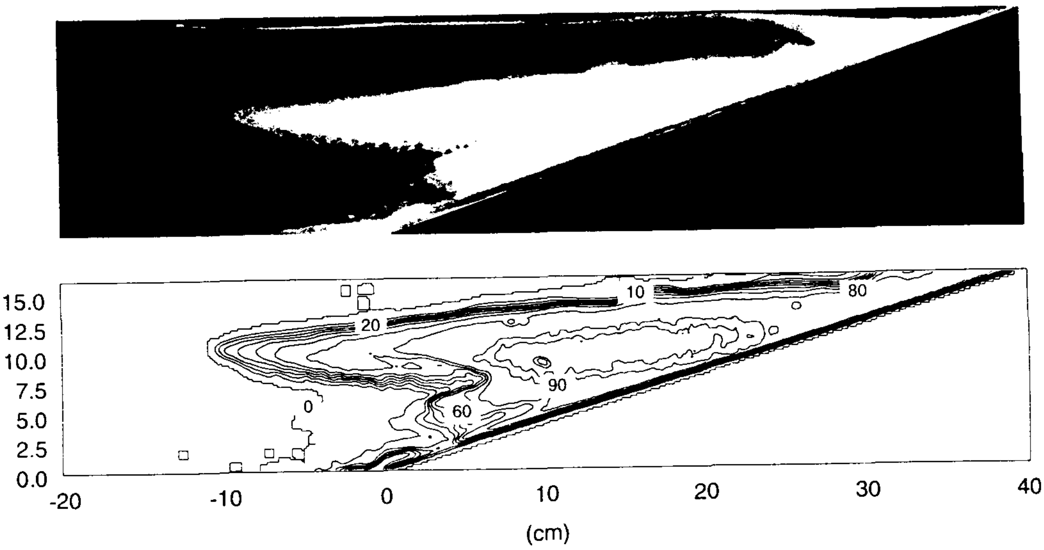


Fig. 6 Relative concentration pattern of the turbid intrusion in the experiment. 80 seconds after the wave generator was started, and three quarters of the photo image were processed.

Resuspension on the slope took place under epilimnion, thermocline and hypolimnion and weak resuspension confined in the hypolimnion caused a turbid bottom current, which was mostly seen in case of pure internal wave and when the boundary mixing was insufficient. Resuspension from other sources drives turbid intrusions in the upper and lower thermocline which were observed under composite waves conditions and the lower intrusion was hard to distinguish from the upper. The lower peak noticed 6 cm above the bottom, did not migrate much as shown in Fig. 8. We tried to make the upper intrusion reduced by removing the clay from the upper part of the slope which was initially under the epilimnion, but we had not reduced it entirely.

Temperature profiles were measured using the 16 thermistors array with the spacing of 1 cm. Thickening of thermocline due to continuous wave mixing separate the upper and the lower sheets by the intermediate layer with a weaker gradient. An evolution of the thermocline in B7 with the wave period of 8.7 seconds was shown in Fig. 7. As initial level of thermocline was lower in this case, the lower sheet went down to the bottom, 3 minutes after the start. The thickening was also a reason for two intrusions above and beneath the original thermocline.

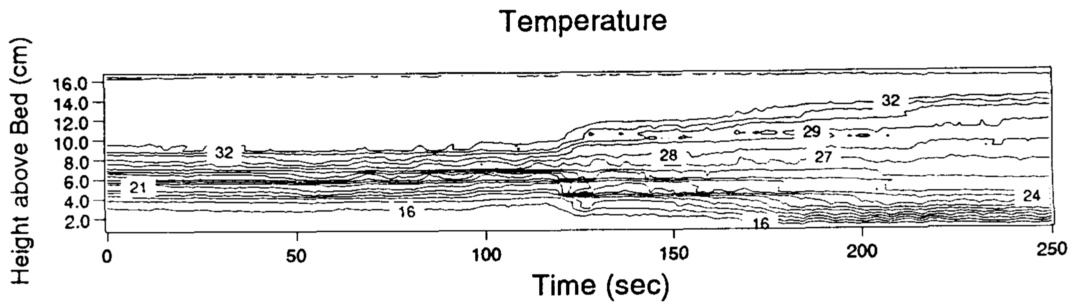


Fig. 7 Evolution of experimental thermocline in the presence of turbid intrusion in the wave tank

Earlier results on the resuspension process observed in the experiments have been shown here. With further consideration on various scales and their similarities, the work would be carried on, but the basic process of resuspension in stratified fluids was made visible.

4. FLUX ESTIMATION

Temporally averaged temperature profiles corresponding to the records in Fig. 2 are shown in Fig. 8, and the thermal staircase was found to be 0.7 m thick. Time difference between the profiles before and after the resuspension was 60 minutes and the profile of the buoyancy flux, transporting warm water downward, was estimated as the time change in the vertically integrated heat content at each level. The flux was calculated assuming the constant thermal expansion for simplicity. Because of the lack of temperature data near bottom, the absolute value of the flux was uncertain, but the difference or the gradient seemed to be estimated properly.

Suppose the staircase was formed by settling of sediment particles within the hour, then the settling velocity, w_s was calculated as $0.7 / 3600 = 1.9 \times 10^{-4}$ m/s, which gives a sediment size of D=15 μm based on the Stokes velocity, $w_s = \sigma g D^2/18\nu$, where σ=1.65 is the submerged specific weight of sediment in water, and ν is the kinematic viscosity. The size was apparent and not really fine, but likely to happen considering the field conditions.

The staircase in the thermocline and the hypolimnion gained heat during the settling, while both the sheets of the upper and lower thermocline lost comparable amounts of heat. Each of the local flux minimums below which the negative buoyancy flux was increasing downward to the local maximum, should correspond to the concentration peak; the lower is of the main intrusion and the upper is probably of the minor intrusion suggested by OBS results, or of locally suspended sediment from the main intrusion. The upper and lower sheets were in the finger regime, where the particles were sinking through region of stable temperature gradient and observed downward heat flux was driven by the settling of sediment. Consequently, the intermediate layer between these finger regions became the staircase until a marginal condition for the diffusive regime was achieved, where stable sediment gradient and neutral temperature gradient were seen.

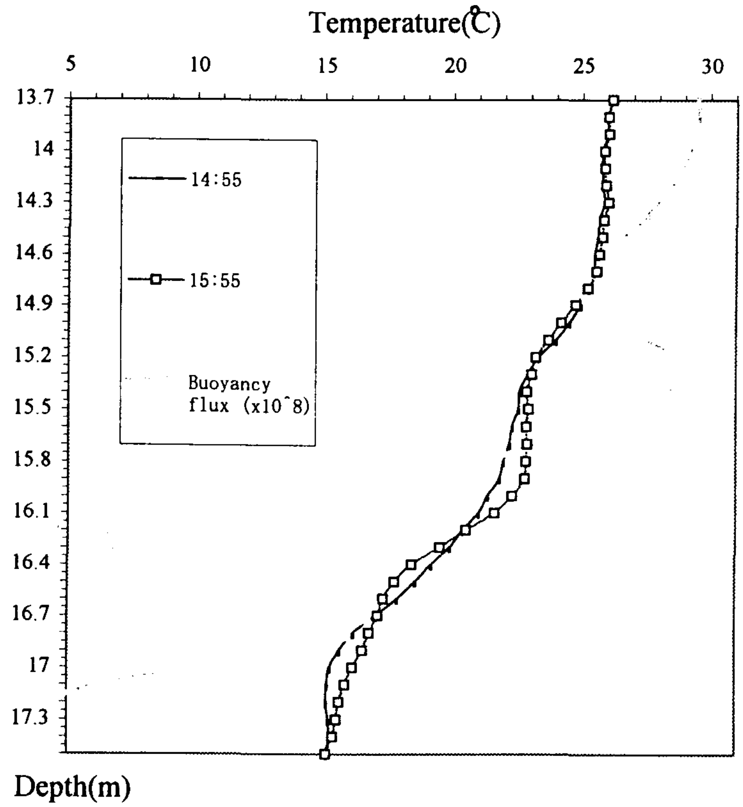


Fig. 8 Temperature and buoyancy flux profiles for the data shown in Fig. 2

Figure 9 shows the temperature record between the data before and after the staircase formation shown in Fig 2. Time interval for the profile sampling was 10 seconds and the resuspension event was seen during this measurement. From the time 15:23 to 15:32, we had a sequence of resuspention every 3 minutes as found in Fig. 3, corresponding to every troughs of the internal wave. A noise at 15:27 was intentionally made when we tried to detect a higher turbidity after the second burst of turbidity fluctuation ceased. Gradation pattern in the figure was used at 0.2°C intervals, and the darker part shows lower temperature within each cycle of integer temperature labeled. Some convective plumes containing colder and turbid water, are seen below the lower thermocline.

The staircase between the 15.3 m and 16.0 m depth, began to be formed in the downwelling phase around 15:30 to 15:40. There could be a larger internal wave with a period of some 30 minutes, because the thermocline were gradually moving upward after 15:40, but in the subsequent profile record of Fig. 2(b), any large scale internal wave was not seen. So other convective motion was thought responsible for the downwelling. The apparent downwelling was 4 x 10^{-4} m/s for the thermal contour of 22.8C. Thus actual vertical velocities in the field should affect on the settling rate of the fine particles.

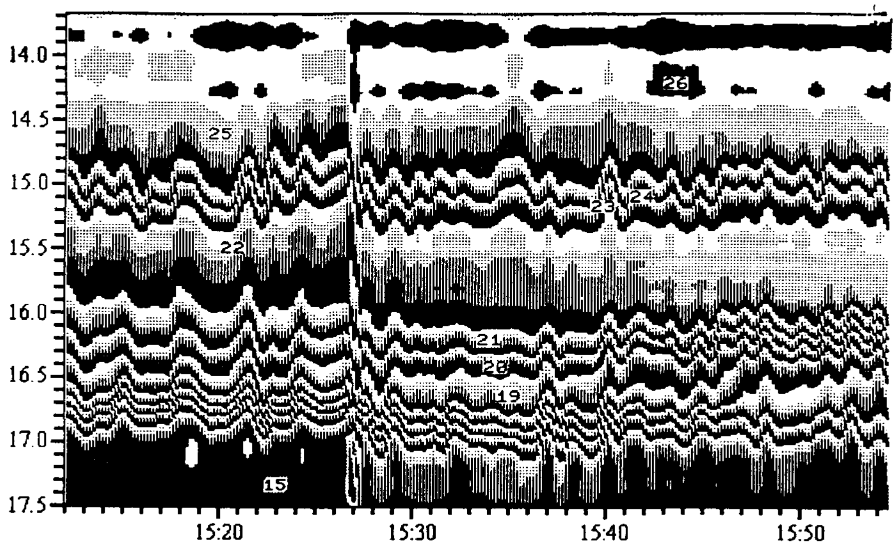


Fig. 9 Temperature record during the resuspension and following formation of the staircase.

According to the 'silt finger' experiment (Okubo et al., 1995), the dependence of the flux ratio, F=Bt/Bs on the density ratio, R= $\alpha\Delta T/\beta\Delta S$ in the finger regime is the same as found in the salt finger experiments as; F=0.91 for 1.05<R<1.5 and F=0.56 for 2<R<10, where α is thermal, and β is sediment coefficient of expansion, ΔT and ΔS are the temperature and the concentration differences within the finger region, respectively. In the experiment, to estimate the sediment buoyancy flux, Bs, in the form of settling rate, an equivalent diameter of 7 μm was selected to fit to the actual reduction in concentration within the upper layer, which is 2 to 3 times larger than the predominant size of the kaolinite particles used.

Turbidity peak at the bottom of the staircase, increased by concentrating sediments in the layer, when the density ratio became small and the possible finger regime of the lower thermocline, became active. The observed thermal buoyancy flux, Bt=5 x 10^{-8} m^2/s^3 were driven by the sediment buoyancy flux, Bs. According to the lower value of flux ratio in the finger regime, F=0.56 when R>2, the sediment flux was simply 8.9 x 10^{-8} m^2/s^3. It should be written in the form, $Bs=\sigma g\Delta Cw_a$, using the vertical advective velocity, w_a. When w_a=1.9 x 10^{-4} m/s, then the volume concentration, ΔC=29 x 10^{-6} was estimated. So the concentration in weight should be ΔS=78 mg/l, which is still within the measured value of turbidity. If the advection w_a is replaced by the real settling velocity of w_s= 5 x 10^{-5} m/s for sediment particle of 7 μm, then ΔS would be 300 mg/l, which is only possible after floods.

Laboratory experiments on the staircases were conducted for both the finger and diffusive regimes in a 1.2 m deep, diffusive tank with a uniform horizontal section of 0.25 m by 0.21 m. Among the experimental conditions, the following was used to produce the staircases in stable thermal stratification. The structure was produced by the surface cooling of the water column under an overstable condition. Taking the long duration after the finger experiment, profiles containing steps were made as shown in Fig. 10, which was characterized by small temperature jumps of 0.1°C, which is rather similar to those observed in the deep ocean. The scale of the experimental staircase was only 2 cm, and it was concerned with the buoyancy flux of Bt=10^{-10} m^2/s^3.

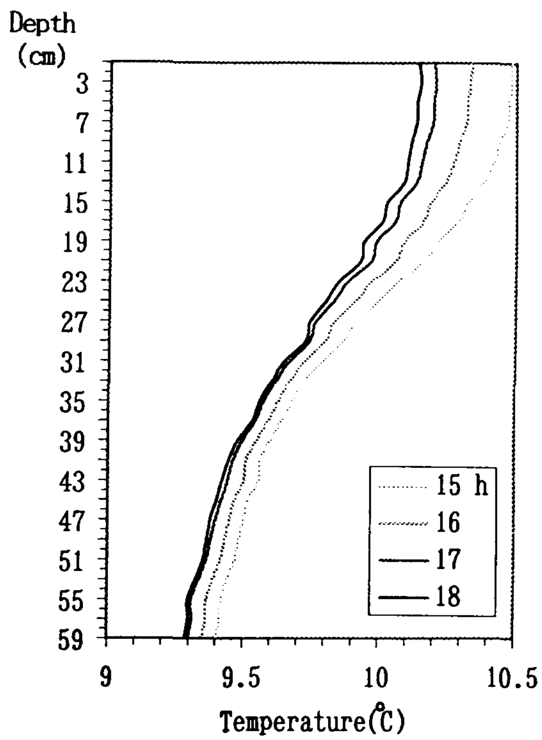


Fig. 10 Laboratory staircases formed in 15 to 18 hours after a finger experiment.

The collaborative measurements were done in the same area of the lake also in September of 1995. An example of ordinary staircase in Lake Biwa was shown in Fig. 11. It was formed far from the bottom and formative process seemed different with the staircase discussed above, but this might be also affected by the sediment which was transported by the intrusion and settling down in the thermocline. A staircase was formed at the bottom of the thermocline and the next was being formed just 1 m above. These structure would be removed soon through the adjustment of the overall density field due to horizontal transport of mutual intrusions.

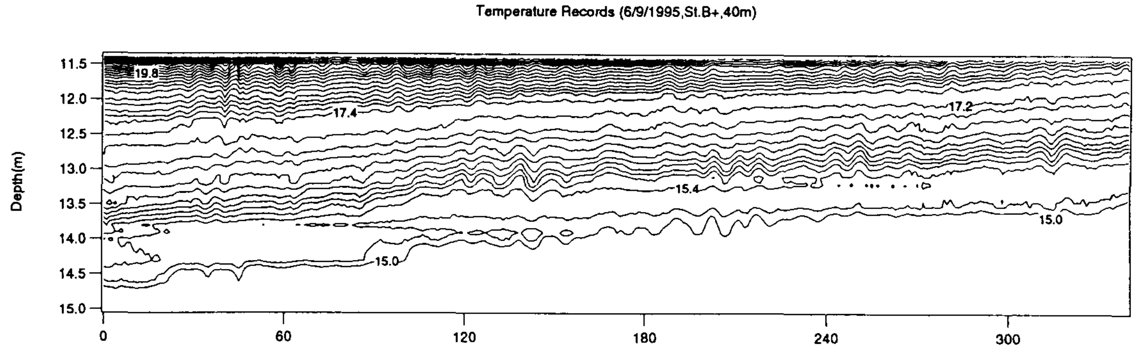


Fig. 11 Ordinary staircase observed in the lower thermocline in the north basin of Lake Biwa.
It was far from the bottom, near the station B, on September 6, 1995.

5. CONCLUSION

The drought in the summer of 1994 affected much on physical processes in Lake Biwa. Turbid intrusion was consistently observed in the lower thermocline, and the peak turbidity was around 10 mg/l, which was the same observed in the resuspension of shallow south basin and but one tenth of that in the intrusion overriding on the thermocline after floods. Turbid intrusion contained also nutrients likely to be from the bottom sediments of the boundary of the lake, and seemed to affect on the biochemical aspects in the lake.

To get a direct evidence of sediment resuspension in Lake Biwa, we measured the bottom turbidity and temperature profiles above the boundary slope at an edge of the thermocline, where the thermocline and the benthic boundary layer interact. Turbidity near the bottom varied intermittently according to the internal wave and the fluctuation was composed of various frequencies ranged from the wind wave to the internal waves. The resuspension process and resultant turbid intrusion were made visible in a laboratory tank, where bottom sediments were found to be suspended under the composite waves condition and both the surface and internal waves are important to enhance the resuspension of the bottom materials. According to the region of resuspension, two kinds of intrusion in the upper and the lower thermocline were expected but those were hard to distinguish in the experiments. Thickening of thermocline had a tendency to make itself heterogeneous and hence to make the lower intrusion intensified as in the case of Lake Biwa in 1994.

The lower thermocline included the turbid intrusion, and the upper thermocline did the minor peak of turbidity but how the latter became to do was not clear. Interfacial waves along the upper thermocline might entrain the sediment particles into the upper layer from the underlying staircase, or minor intrusion on the day could deliver sediments to the site. There seemed to be, anyway, two peaks in the turbidity profile in the divided thermoclines after the resuspension, therefore there were two potential finger regions. While in the mid thermocline portion between those finger regions, there passed the remarkable heat flux downward and it was thought to be driven by the settling flux of sediment. Apparently the turbidity was too low to drive effective fingers, but the particles concentrated to the intrusion and vertical advection due to internal motions and larger scale convections, which are several times higher than the settling velocity of the silt particles of a few micron would easily affect on the concentration. The settling rate at the bottom of the staircase was estimated assuming the finger regime of double-diffusive convection. The layer became isothermal during the downwelling of some 30 minutes.

The staircase was with large temperature jumps of a few degrees in the upper and lower sheets, because those were the parts of stable thermocline formed in the hot summer. The shape was similar and the thickness was one-tenth, but the temperature difference was strikingly large comparing with the oceanic staircases with the jumps of 1°C. Multiple thermal staircases structure with jumps of 0.1°C, was reproduced in the diffusive tank, which was rather similar to deeper thermohaline staircases in the oceans. Another staircase beneath the seasonal thermocline in Lake Biwa observed in 1995, was with the temperature jumps of the order of magnitude. The thickness and jumps of staircases vary widely depending on the thermal buoyancy flux and the concentration or the gradient of silt as well as salt.

When the double-diffusive convections are effective enough in vertical transport in lakes, simple diffusion model does not work properly. The process is highly complicated including horizontal transports due to intrusions as intermediate density currents as well as the vertical motion accompanied by internal waves and convections. It was considered as an effective process to feed nutrients into the water. In Lake Biwa, only an hour was needed to form the sheets and the layer, and it should disappear being adjusted by mutual intrusions. Our resultant concern is how the biochemical concentrations are affected by the double-diffusive process driven by the buoyancy scalars.

Acknowledgment

We thank Prof. Masami Nakanishi who encouraged us to measure the thermal process in the lake under the drought condition in 1994. He was also the leader of collaborative field experiment supported by the Scientific Research Fund from the Ministry of Education, Science and Culture. His logistic support allocating the research vessel, Hasu, belonging to the Center for Ecological Research, Kyoto University, are much appreciated. The laboratory experiment on the turbid intrusion was conducted at the Department of Civil Engineering, Kyoto University, where the second author have carried on the experiment owing valuable discussion and helpful comments by his supervisor, Prof. Yoshio Muramoto. The second experiment has been improved at the hydraulic laboratory in the Department of Environmental and Civil Engineering, Okayama University. The fact that a part of the experiment was supported by the fund from NISSAY foundation should be mentioned here with thanks.

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