Stratification of very deep, thermally stratified lakes

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Abstract

In very deep freshwater lakes, deep recirculation presents itself with remarkable differences to shallower lakes. We consider the stratification where density gradients are exclusively due to temperature differences. The annual circulation patterns are discussed for various climatic conditions. Very deep lakes do not necessarily produce full overturns during T_{md} transition in autumn and spring. Peculiarities of the stratification are derived for cases, in which surface temperatures cross 4°C during the annual cycle: Firstly, the asymmetry between autumn and spring circulation, secondly, the proximity of temperature to the T_{md} profile, and thirdly, the isothermal deep water. We compare conceptual model results of horizontally homogeneous lakes with measurements in very deep caldera lakes in Japan (Lakes Ikeda, Tazawa, Toya, Kuttara and Shikotsu). Between oligomictic lakes and thermobarically stratified lakes, we have found lakes circulating reliably despite their enormous depth. We discuss susceptibility to climate variability supported by comparisons with single point measurements from the 1920s and 1930s.

1. Introduction

Recirculation is one of the controlling factors for the ecological evolution of lakes. Incomplete deep recirculation, for example, can result in anoxic bottom waters. As a consequence, organisms relying on oxygen for respiration are excluded from these layers. Anoxia can be decisive for releasing substances from the sediment, such as phosphorus as a well-known example. Hence recirculation patterns can crucially interfere with the trophic evolution of lakes. In addition, a bottom water body can store high amounts of nutrients and other dissolved substances of environmental concern. Released by an extraordinary mixing event, these substances can be hazardous for organisms inside and around the lake.

Only lakes of limited depth reliably produce a full overturn every year. Lakes can be meromictic due to gradients of dissolved substances (e.g. Findenegg, 1935, Hutchinson 1957, Boehrer and Schultze, 2008), they can be oligomictic due to interannual variability of the weather conditions, and thirdly they can be permanently stratified due to pressure effects, if they lie in the corresponding climatic zone. Temperature profiles in Lake Mjøsa, Norway (Strøm 1945), Lake Ladoga, Russia (Pettersson 1902) and Crater Lake, USA (Kemmerer et al., 1924) proved the presence of thermobaric stratification in freshwater lakes, when climatic and morphometric conditions allowed for it.

Our interest was directed towards “very deep” lakes, which, in this contribution, refers to lakes deep enough to show the discussed stratification features. We only included lakes where stratification and circulation were controlled by heat. The investigation covered both lakes with surface waters traversing the temperature of 4°C in the annual cycle, in contrast to lakes where surface waters stayed warmer than 4°C all year. Former lakes could show a stratification due to pressure effects. In two cases, i.e. Crater Lake in Oregon, USA (Crawford and Collier, 1995, Crawford 2005) and Lake Baikal, Siberia, Russia (Weiss et al. 1991, Carmack and Weiss 1991, Imboden and Wüest 1995, Wüest et al 2005), the stratification and the deep water renewal had been investigated in detail, though many more such lakes are known (Boehrer and Schultze 2008, see above).

In contrast to considerations made by Carmack and Weiss, we investigated lakes where horizontal gradients were minimal and hence thermobaric instabilities were minimalized. To keep horizontal differences small, we searched for lakes of small horizontal dimensions. This study on circulation patterns of very deep lakes became especially interesting, as worldwide mine lakes of similar shape and size have come and will come into existence within the following few years or decades (e.g. Island Copper Mine, BC, Canada; Berkeley Pit, Montana, USA; Hambach and Garzweiler, Germany).

2. Model of horizontally homogeneous, purely temperature-stratified very deep lake

Generally water movements in lakes are three dimensional, and gradients of dissolved substances contribute to the density stratification. On purpose, we approach the circulation of very deep lakes with most simple boundary conditions to test and enhance our understanding of processes. The best approximation for density if temperature T and salinity S are known is by Chen and Millero (1986); for a more comprehensive display see Boehrer and Schultze (2008).

Salinity is evaluated from electrical conductivity measurements following the freshwater assumptions of Chen and Millero (1986). Including compression under hydrostatic pressure *p*, yields in-situ density $\rho_{in-situ}$. The compressibility of water is a function of temperature: higher compressibility at low temperatures makes T_{md} (temperature of maximum density) shift to smaller values at a higher pressure. Chen and Millero present an equation to calculate the temperature of maximum density for low salinity water: $(\partial\rho_{in-situ} / \partial T_{pot})_{p,S} = 0$:

$$T_{md} = 3.9839 - 1.9911 \cdot 10^{-2} p - 5.822 \cdot 10^{-6} p^2 - (0.2219 + 1.106 \cdot 10^{-4} p)S \qquad (1)$$

The contributions of the salinity term and the term second order in pressure lie in the range of 10 mK or smaller for our investigated lakes. T_{md} falls by about 0.2 K over 100 m depth in freshwater. Drawn as a profile, T_{md} divides the T-p domain into two half-plains (see Fig.

1). Right (or below) the T_{md} profile, stable density stratification is achieved, when warmer water overlies colder water. Left of the T_{md} profile, colder water overlies warmer water for stable conditions, under the precondition of no salinity gradients in the vertical.

Our conceptual model applies to moderate and higher latitudes, where surface water temperatures are noticeably different in summer and winter. We distinguish two cases: case 1, climates, in which surface water temperatures are always higher than 4°C, and case 2, climates, in which surface temperatures cross 4°C twice a year. Geothermal heat flow through the lake bed into the water body is permitted. Mixing is implemented until stable conditions are reached.

Case 1: Starting from homogeneous conditions in winter, surface water is heated by radiation and contact with the atmosphere (spring, Fig. 1a). Mixing - usually driven by wind – shifts the thermocline to greater depths (summer), until in autumn lower surface temperatures allow much deeper recirculation. If surface water temperatures fall below deep water temperature, the entire water body can overturn. However, only winters cold enough can force full overturns. Milder winters result in a limited recirculation depth (oligomixis), if additional forces, such as wind, fail to eliminate remaining density differences. Depending on the amount of energy available for mixing, this annual cycle can also be valid for lakes with deep water temperatures slightly below 4°C.

In case-1 climates, particularly cold winters form unusually cold deep waters. As a consequence, overturns in subsequent winters are less probable, until geothermal heating through the lake bed and diffusive heating from above raise deep water temperatures to more usual values. In addition, increasingly warmer winters, as now anticipated for many regions on Earth, can contribute to less frequent overturns, as bottom waters have been formed under still colder conditions.

Case 2: Lakes reaching surface temperatures noticeably smaller than 4°C can stratify “inversely”, with a mixolimnion above less cold deep water (winter/spring, Fig. 1b). For stability reasons the temperature gradient lies above the T_{md} intersection. Carmack and Weiss (1991) have investigated this kind of stratification while focussing on boundary conditions given in Lake Baikal. They have shown that direct wind action or internal waves can move inverse temperature gradients vertically across the T_{md} profile. In such a case, density stratification is unstable within the affected area and large volumes of mixolimnetic waters can intrude the deep water. This process is called thermobaric instability and leads to episodic partial deep water renewal.

In contrast to the findings of Carmack and Weiss (1991) and Weiss et al. (1991), our conceptual model does not permit horizontal gradients. We simulate the stratification in lakes in the absence of thermobaric instabilities. Our model enforces stable density stratification while implementing an annual cycle of surface temperatures. Proceeding from winter into spring (Fig. 1b), increasing surface temperatures imply unstable conditions. As a consequence, the entire mixolimnion follows the temperature evolution of the surface water until reaching deep water temperature. Only if sufficient forcing acts on the lake at this moment, overturning is possible, but chances for a full overturn are small.

With a further temperature increase at the surface, stratification is unstable only down to T_{md}. Without any additional mixing, the deeper mixolimnion will not participate in the circulation. A further quasi-steady increase of surface temperatures results in temperature profiles reproducing T_{md} closely over a large depth range in spring (see also Weiss et al. 1991). After summer stratification and autumn, lakes can go into inverse stratification in winter, without necessarily going through a homothermal phase (Fig.1b). If mixing and convection due to warmer surface temperatures at the end of winter are sufficient to homogenize the mixolimnion, the lake establishes a two layer phase (Fig. 1, winter/spring). In this case, the depth of the recirculation does not only determine the thickness of the remaining deep water but also its temperature as T_{md} of the recirculation depth: Higher deep water temperatures imply unstable conditions in the temperature gradient.

Deep water continuously acquires heat from the lake bed (geothermal) and from spring to early winter from warmer waters above. Only when the waters above are colder, heat can escape again. When heat leaves through the upper boundary, the deep water becomes unstable and is homogenized when all acquired heat has left (1-dimensional!). Deep water temperatures do not reflect winter temperatures of surface waters, but depend on the circulation depth during the transition from winter to spring. Extreme events such as extremely cold or mild winters do not directly impact on deep water renewal. The crucial time for mixolimnion waters to intrude into the deep waters is the short period when surface temperatures cross deep water temperatures at the transition from winter to spring.

3. Field Sites and Results

We searched for lakes deep enough to show pressure effects of T_{md} which would represent conditions of horizontal homogeneity and pure temperature stratification as well as possible. A series of caldera lakes in Japan seemed suitable, as they had small horizontal dimensions (diameters between 2.5 km and 12 km) in comparison with their great depths (148 to 423m). From South to North and warm to cold, we took measurements in lakes Ikeda, Tazawa, Toya, Kuttara and Shikotsu (map see Boehrer et al. 2008). Geographic location and general morphological features have been listed (Table 1). None of the lakes showed conductivity gradients large enough to control the circulation pattern.

Measurements were performed with an Ocean Seven 316 multiparameter probe (Idronaut, Italy) at the deepest locations of the lakes just after stratification had established in spring 2005. For data confirmation, a CTD probe (Sea & Sun Technology, Germany) was attached. Within the expected accuracy, the probes showed the same profiles (for more details see Boehrer et al. 2008).

Lake Ikeda, the most southern and warmest lake, did not mix completely in 2004 / 05. It was oligomictic and had not turned over since 1986 (Hirae et al., 1997). Oxygen depletion had occurred at the bottom by 1989. In 2005, no oxygen was present in the deep waters below 120m depth (see Fig.2).

Lake Tazawa and Lake Toya had obviously experienced full overturns in 2004 / 05, as concluded from the absence of gradients in oxygen (Fig. 2), el. conductivity and pH (Boehrer et al. 2008) profiles. Deep waters in Lake Tazawa, lay above 4°C at all depths, while in Lake Toya deep waters were colder than 4°C (Fig. 2). In conclusion, Lake Tazawa had experienced a full overturn at temperatures just above 4°C, while Lake Toya did so at temperatures just below 4°C.

Lake Shikotsu showed nearly homogenous profiles of dissolved oxygen (Fig. 2); el. conductivity and pH (see Boehrer et al. 2008). However, a small but distinctive step could be verified in the profiles. This indicated that recirculation did not include the waters below. The depth of this step coincided with the point in the temperature profile below which no temperature gradient was found.

Lake Kuttara also showed these features, though less impressively due its smaller depth. Recirculation had left distinctive steps in oxygen and el. conductivity (see Boehrer et al. 2008) at 125 m depth with isothermal waters below. In both, Lake Kuttara and Lake Shikotsu, we find temperatures close to T_{md} over a wide depth range.

4. Discussion

The confirmation of the oligomictic type of circulation with Lakes Ikeda was not particularly surprising. Lake Ikeda had not circulated since 1985/86. Comparing winter air temperature with deep water temperature over 20 years, Hirae et al. (1997) already reasoned that this long period of no overturn in Lake Ikeda could only partly be attributed to global warming. Probably the overturn in 1985 / 86 must be considered an extreme event which produced cold bottom waters, which require many years of diffusive heating before a winter of more usual surface water temperatures can force an overturn again. Lakes Tazawa and Toya probably experienced a full overturn in 2004 / 05, one above and one below 4°C.

Lake Shikotsu reflected the type of circulation for colder regions, as did Lake Kuttara but less convincingly due to its smaller depth. Both lakes showed temperatures approaching the T_{md} profile over a large depth range and isothermal deep water below. Though there was no full overturn, deep water bodies presented themselves as well supplied with oxygen and well circulated within themselves.

The very deep caldera lakes in Japan were among the first where thermobaric stratification had been found. Most of these measurements in the years between 1910 and 1931 had been conducted with insulated water bottles or reversing thermometers. Yoshimura (1936a, b, c), who published these data or cited some from more difficult to attain sources, very cautiously estimated an accuracy of 0.3 K for all measurements done in 1930 or earlier and an accuracy of 0.1 K for measurements after 1930. Already Strøm (1945) indicated also the earlier measurements could be trusted within 0.15K.

We included the early measurements deeper than 100 m, together with our profiles. The direct comparison showed higher temperatures in Lake Ikeda, which suited the expected susceptibility of deep water temperatures in oligomictic lakes to different air temperatures. Lake Shikotsu showed no change in temperature. Interestingly, Lake Tazawa had shown slightly lower temperatures 80 years before (2005 above 4°C, then below 4°C), and Lake Toya showed the reverse case (2005 below 4°C, then above 4°C). Possibly connected to the vanishingly small thermal expansion coefficient, even very deep lakes can overturn within a certain band of temperatures of around 4°C.

Typical features of thermobarically stratified lakes, such as homogeneous deep water and close reproduction of T_{md} could be explained under the simple assumption of pure temperature stratification, depth dependent T_{md} and stability arguments. They were supported with field measurements and hence were typical under the given (climatic) boundary conditions. Heat transport into and out of the deep water of e.g. Lake Shikotsu could not be one dimensional. Though present, this three-dimensionality did not manifest in the larger scale stratification.

Also Crater Lake in Oregon, USA of a similar shape as Lake Shikotsu although slightly larger reflected some of the features, though a salinity gradient preserved a small temperature gradient in the deep water. The validity of our one dimensional conceptual model was naturally limited to cases where salinity gradients and horizontal gradients did not impact on the stratification, as in the much larger Lake Baikal for example (Carmack and Weiss 1991, Wüest et al. 2005). Our conceptual model, however, is well capable of reproducing most typical features of thermobaric stratification in lakes of several kilometres diameter and several hundred meters depth.

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Figure captions - (Figures now in separate files;
Fig 1: Color version for online edition, and Black-and-white version for print
Fig 2: Color version for online edition, and Black-and-white version for print
Fig. 3 one black and white version for both)

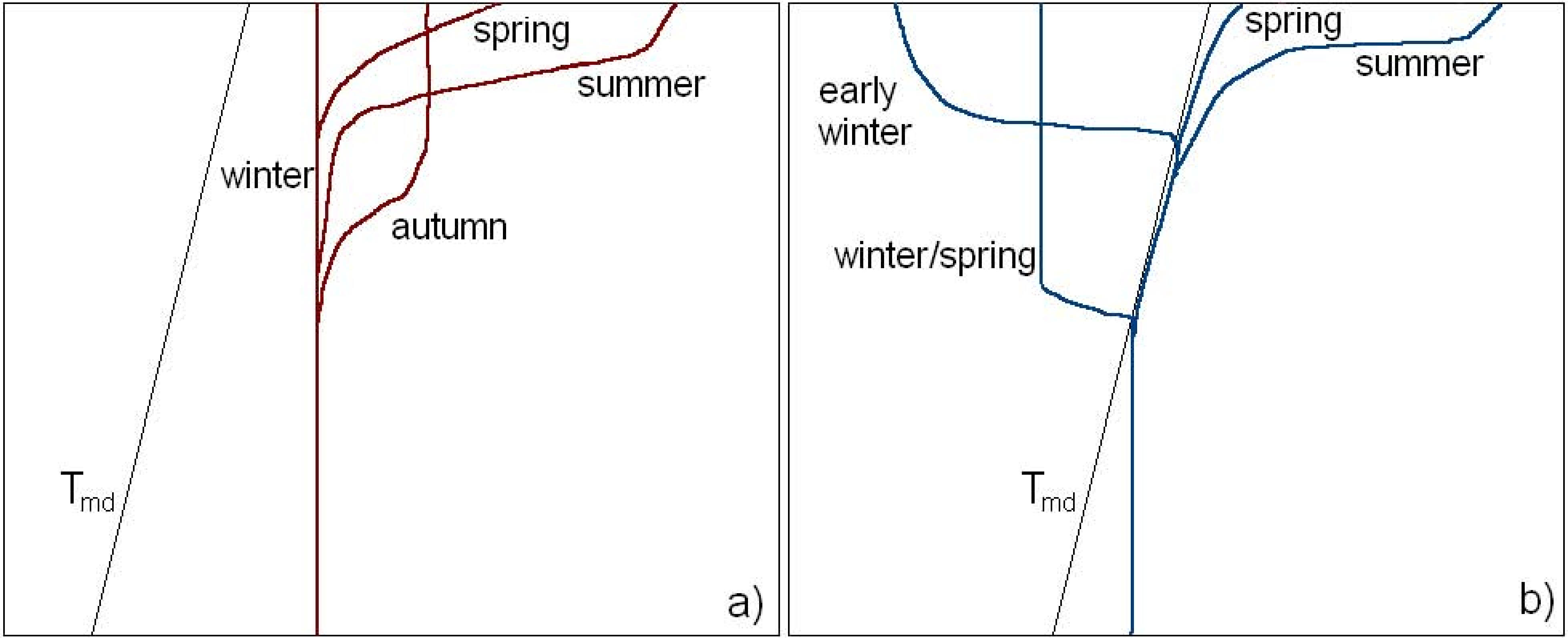
Figure 1: sketches of temperature profiles of thermally stratified lakes at various seasons as concluded from a horizontally homogenous conceptual model. a) Surface water temperature always stays above 4°C. b) Surface water temperature crosses 4°C. T_{md} represents temperature of maximum density at the respective depth.

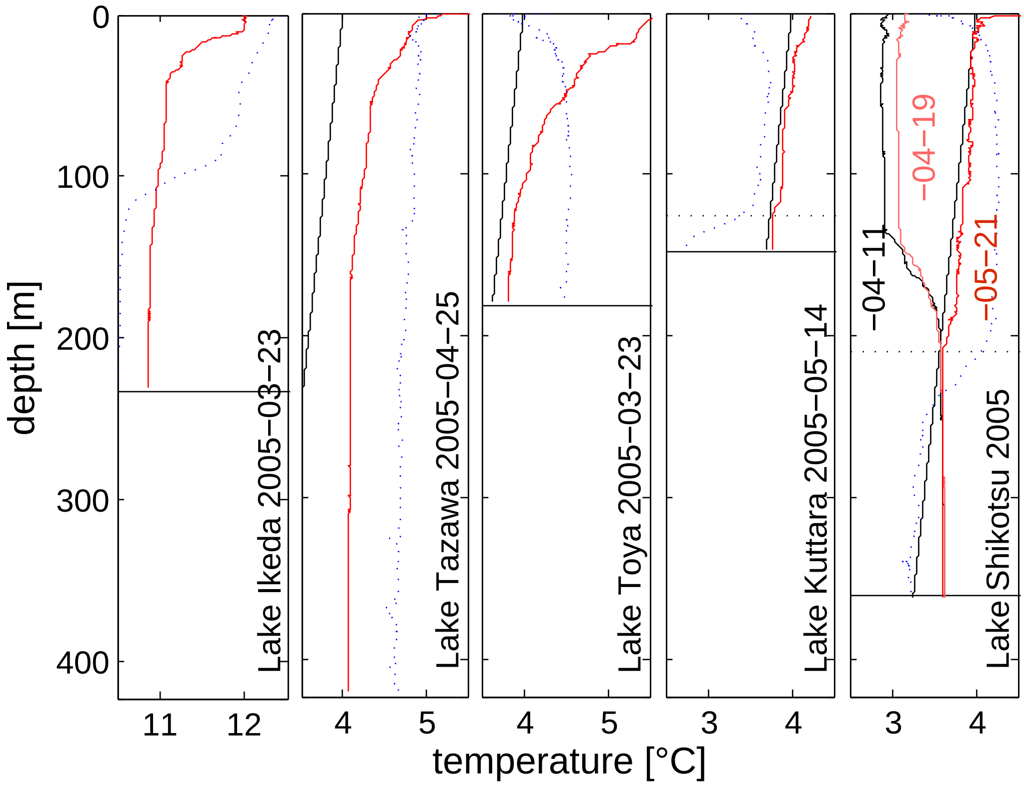
Figure 2: Temperature profiles of very deep caldera lakes in Japan during spring 2005. Fine lines indicate temperature of maximum density (T_{md}) against pressure, broken horizontal lines show the recirculation depth as seen in Lake Shikotsu in winter profiles intersecting T_{md} and as suspected for Lake Kuttara. Oxygen profiles are shown as broken lines (full panel width 0 to 10 mg/l for Lake Ikeda; 10.5 to 12.5 mg/l for lakes Tazawa and Kuttara; 11.5 to 13.5 mg/l for lakes Toya and Shikotsu, see also Boehrer et al. 2008)

Figure 3: Temperature profiles of deep caldera lakes in Japan during early spring 2005 (solid lines) compared to point measurements around 1930 in winter / early spring (stars) and summer (circles Yoshimura 1936a, b). The fine line shows T_{md}. Measuring dates: Shikotsu: 18 Apr 1915, 1 Aug 1922 and 22 Aug 1931 (diamonds); Kuttara 27 Mar 1917 and 5 Aug 1928; Toya 9 Feb 1918, 25 Aug 1925 and 6/7 Aug 1928 (diamonds); Tazawa 11 Mar 1926 (stars), 23 Jul 1931 (circles) and 26 Aug 1931 (diamonds); Ikeda 8 Apr 1930 (stars) and 4 Aug 1927 (circles)

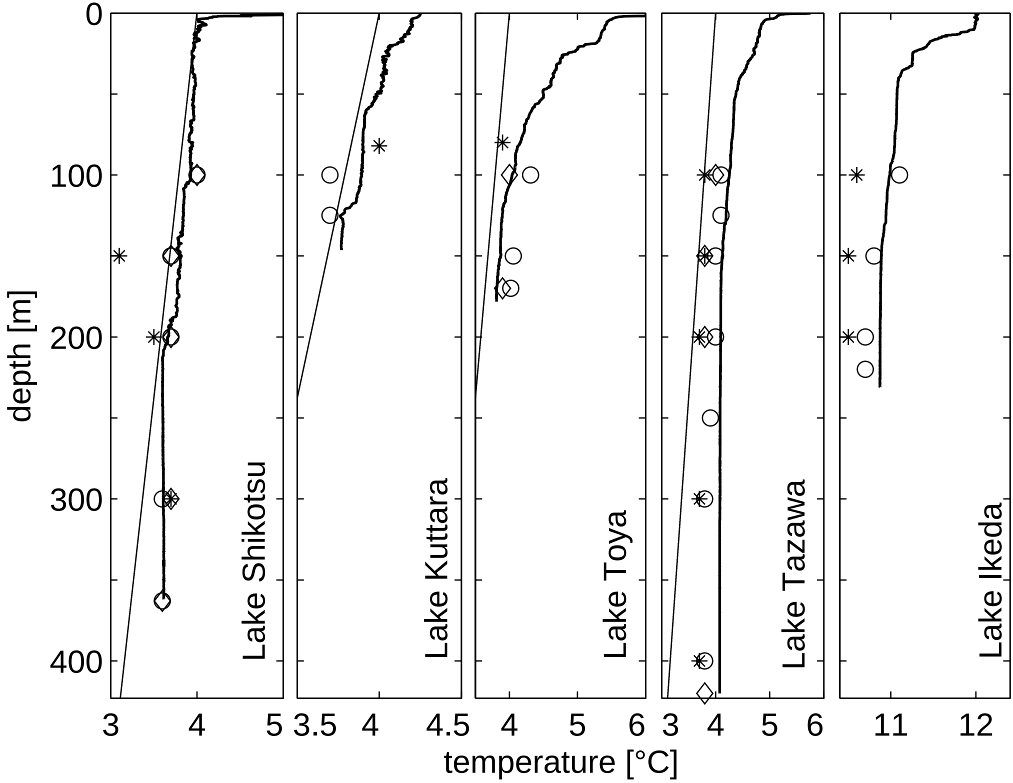
Table 1: investigated lakes, morphology and location of measuring points

Lake name	max. depth [m]	surface area [km²]	altitude [m asl]	region	North n° n' n"	East n° n' n"	el.conductance κ_4 [μS/cm]	stratification & mixing pattern
Ikedako	233	11	88	Kyushu	31 14 08	130 33 51	58	oligo- /mero-
Tazawako	423	25.7	250	Tohoku	39 43 13	140 39 43	67	holo-
Toyako	181	70.4	84	Hokkaido	42 37 05	140 52 49	97	holo-
Kuttarako	148	4.72	258	Hokkaido	42 29 57	141 11 13	39	th-baric
Shikotsuko	363	78.8	248	Hokkaido	42 46 13	141 21 19	131	th-baric


spring
summer
winter
autumn
T_{md}
a)
spring
summer
early
winter
winter/spring
T_{md}
b)



depth [m]
temperature [°C]
Lake Ikeda 2005−03−23
Lake Tazawa 2005−04−25
Lake Toya 2005−03−23
Lake Kuttara 2005−05−14
Lake Shikotsu 2005
−04−11
−04−19
−05−21



depth [m]
0
100
200
300
400
temperature [°C]
3
4
5
3.5
4
4.5
4
5
6
3
4
5
6
11
12
Lake Shikotsu
Lake Kuttara
Lake Toya
Lake Tazawa
Lake Ikeda