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Entrainment, annual circulation and groundwater inflow in a chain of lakes as inferred by stable ^{18}O isotopic signatures in the water column

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ABSTRACT

The stable oxygen isotopic signature $\delta^{18}O$ of water has been proved to be a useful marker in hydrological lake studies. However, it is applied only sporadically to determine the extent of mixis and stratification, which is vital for all hydrological and limnological studies. We present a study of the changes in $\delta^{18}O$, temperature and Schmidt stability in the water column of three adjacent lakes of very different mixis types (polymictic to meromictic) over almost one year (May 2008 to April 2009). The response of $\delta^{18}O$ to important hydrologic processes (entrainment, stratification, circulation, groundwater inflow) and weather influences (cooling period, ice cover and melt water inflow) is discussed. The lakes are part of the Osterseen chain of lakes south of Munich, Germany. Although hydrologically connected, these lakes show various mixis types (polymictic to meromictic) due to large differences in size, groundwater inflow and water renewal time. Polymixis and the strong subsurface inflow of groundwater in Lake Waschsee (25.6×10^3 m^3) were indicated by the same trends in the $\delta^{18}O$ signature throughout all water layers and by the mean overall signature (-9.94‰) being very close to $\delta^{18}O$ of local groundwater (-10.01‰ ± 0.06). $\delta^{18}O$ signatures of the larger dimictic Lake Fohnsee (2298.3×10^3 m^3) revealed a highly significant trend towards lower values of $\delta^{18}O$ in its hypolimnion, indicating inflow of groundwater. A cooling period during the summer stratification characterised by high wind speeds resulted in a considerable drop of lake surface temperatures and Schmidt stability (up to 25%) in lakes Fohnsee and Eishaussee and was followed by a deepening of the mixed upper water layer and entrainment of hypolimnetic water layers. This was clearly shown by a signal change in deeper water layers formerly constant in $\delta^{18}O$. The permanent meromixis present in Lake Eishaussee (297.0×10^3 m^3) could also be confirmed by isotopic signatures, as bottom water layers remained significantly isolated in $\delta^{18}O$ from the remaining water column over the whole study period. We summarize that the oxygen isotopic signature of water is an easy to interpret, excellent indicator of important hydrologic processes in a lake and can readily be integrated into routine sampling. The present findings will further contribute to the analysis of hydrological data as well as to the interpretation of paleoclimatic reconstructions using proxies of lake water $\delta^{18}O$.

Key words: circulation, meromixis, entrainment, Schmidt stability, stable isotopes, $\delta^{18}O$

1. INTRODUCTION

The dimictic state with a pronounced thermal stratification of water during summer is considered a reference situation for the vast majority of lakes in temperate regions of low to mid altitude (Wetzel 2001).

Summer stratification has a drastic effect on nearly all biological, chemical and physical processes in a lake, especially on the trophic situation and primary production (MacIntyre 1993; Salmaso 2005). As the degree and the stability of the summer stratification are a function of density differences mainly dependent on water temperature and salinity (Chen & Millero 1986; Boehrer & Schultze 2009), many researchers only used the water temperature signal to study mixis in lakes (e.g., MacIntyre 1993; Ambrosetti *et al*. 2001). A good indicator for the extent of stratification in a lake is the stability index S *sensu* Schmidt (Kjensmo 1994), which is calculated from density differences in the water column. It is a measure of the energy that would be necessary to mix a thermally stratified lake so as to create a new isothermal state without further addition or loss of heat (Ambrosetti *et al*. 2001).

It is mainly dependent on surface water temperature (Barbiero *et al*. 1997), which in turn is strongly influenced by air temperature. Therefore, cooling periods within the summer stratified season can produce a considerable drop in stability, which may present a precondition for but not necessarily the result of windinduced mixing in an isothermal epilimnion. Although having little or no effect on the physical properties, the latter can have a significant impact on the intensity of primary production, as it causes vertical entrainment and internal loading of phosphorus to the epilimnion (Barbiero *et al*. 1997; Soranno *et al*. 1997; Carstensen *et al*. 2004).

The use of the stable isotopic signature of the elements of water as a marker of hydrological processes in lakes has a long and successful history: Since the initial description of the systematic variations in the isotopic composition of meteoric waters worldwide by Harmon Craig in 1961, the stable isotope method has found widespread application in hydrology, especially in lake water balance investigations (e.g., Craig 1961; Dincer 1968; Gat & Bowser 1991; Mayr *et al*. 2007; Yi *et al*. 2008).

Together, stable isotopes of hydrogen and oxygen form the different isotopomeres of water ($^2H^1HO/^1H_2O$ and $H_2^{18}O/H_2^{16}O$). Due to slight differences in their molecular diffusivity and saturation vapour pressure (Dincer 1968; Gibson *et al*. 2002), evaporation leads to heavy isotope enrichment of the remaining water. Because of their position in the water cycle, inland waters tend to be depleted in the heavy isotopomeres relative to the isotopic composition of sea water (Gat 1996). Accordingly, further evaporation leads to an amount of isotopic re-enrichment in the lake water representative for its respective balance of inflow and evaporation (Gat & Bowser 1991; Gibson *et al*. 2002; Mayr *et al*. 2007). The isotopic equilibrium value of a dimictic holomictic lake integrates over all hydrological influences and is only apparent during annual circulations (Gibson *et al*. 2002; Stichler *et al*. 2008). During summer stratification, the signal of isotopic enrichment due to evaporation on the lake surface is constrained to the mixed upper layer, while the signal in the hypolimnion remains constant or might even be subjected to a slight depletion proportional to subsurface inflow of groundwater with a more negative isotopic signature. An informative overview of these processes can be found in the introduction of Gibson *et al*. (2005).

Stable isotopes of oxygen and hydrogen are well suited for investigating lake stratification and circulation, since they can be easily integrated in routine water sampling. They are universally existent and therefore applicable when compared to the limits of artificial tracers (e.g., Holzner *et al*. 2009). Moreover, the response of the signal is highly specific and only occurs in the case of significant mass transport of water (Dincer 1968).

Despite this, the information provided by the isotopic signal about the degree of stratification of the water column has been used rather hesitantly and only as a by-product of water balance investigations (e.g., Hostetler & Benson 1994; Gupta & Deshpande 2004; Delalande *et al*. 2005; Mayr *et al*. 2007; Caliro *et al*. 2008; Hofmann *et al*. 2008; Stichler *et al*. 2008).

Only recently, the potential of the oxygen stable isotopic signatures for studying stratification and turnover processes in lakes has been demonstrated by Perini *et al*. (2009), who used this signal for a qualitative estimation of the perennial development of circulation, stratification, and groundwater inflow in 6 Italian lakes.

Here, we describe the progressive annual changes (May 2008 to April 2009) of the oxygen isotopic signature in the water column of three adjacent lakes with different hydrology (polymictic to meromictic). The response of the signal to entrainment events and groundwater inflow is also discussed.

We show that the oxygen isotopic signature $\delta^{18}O$ of water is an easy to interpret, excellent indicator of important hydrologic processes in a lake and can readily be integrated into routine sampling.

2. MATERIAL AND METHODS

2.1. Study site

The Osterseen chain of lakes (Fig. 1) is located at the southern end of Lake Starnberg south of Munich, Germany. It consists of 20 individual, but hydrologically connected lakes. Formed after the rapid disintegration of the Würm glacier ice shield at the end of the last Ice Age, the lakes share a very similar kettle-like basin morphology with the deepest point beneath the centre of the lake surface (so called 'Toteisrestseen', Rothpletz 1917). The lakes are fed almost exclusively by subsurface groundwater inflow which in some lakes is quite strong and has a noticeable effect on hydrology and mixis type (Melzer 1976). Accordingly, water renewal time also varies from lake to lake.

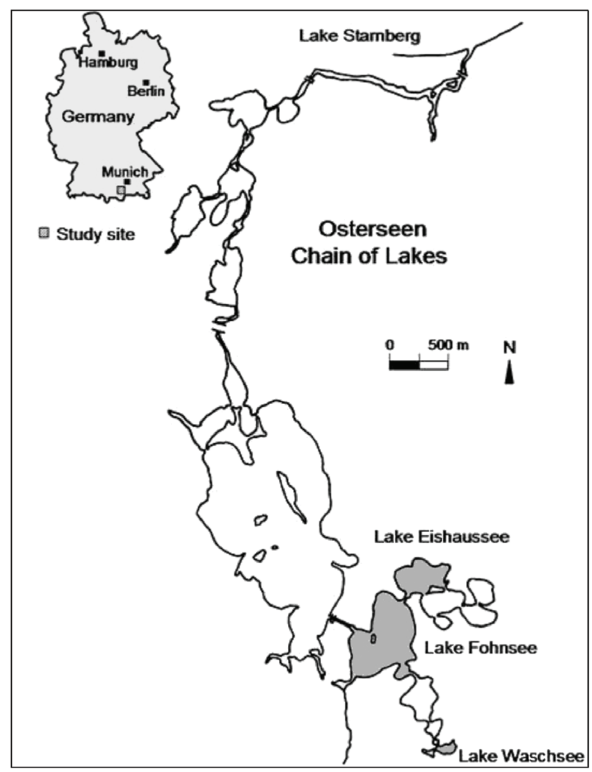

Fig. 1. Outline map of the geographic location of the Osterseen chain of lakes. The investigated lakes are highlighted with an grey filling.

In this study, the oxygen isotopic signal in the water column of three selected lakes was monitored over the course of almost one year (May 2008 to April 2009). Those lakes, namely lakes Waschsee, Fohnsee and Eishaussee (see Fig. 1), differ markedly in size and hydrologic properties (see Tab. 1).

Tab. 1. Basic morphometric and hydrologic parameters characterizing the investigated lakes in the Osterseen chain of lakes with an elevation a.s.l. of 594 m (data from Zorell (1943). *as indicated by our results.

Parameters	L. Waschsee	L. Fohnsee	L. Eishaussee
surface area (m^2)	8500	211,900	34,148
volume ($\times 10^3$ m^3)	25.6	2298.3	297.0
max depth (m)	5.4	23.7	19.6
mean depth (m)	3.0	10.8	8.7
ground water inflow	very high	*significant**	none
water residence time	*very low**	*high**	*very high**
mixis type	polymictic holomictic	dimictic holomictic	dimictic meromictic

2.2. Sampling and measurements

Conductivity (µS cm^{-1}) and temperature (°C) profiles were taken in 2 m intervals at the deepest point of each lake with a multi-parameter probe (WTW Multi 350i). Measurements were carried out about every two weeks in the period from March 2008 to April 2009 (15-16 samplings). A lead weight (1.5 kg) was attached to the multi-parameter probe to avoid potential error in depth due to wind drift of the boat. The water samples for analysis of oxygen isotopic signature were taken in the same depths on the same occasion immediately after the temperature measurements, but not before 21.05.08 (11-12 samplings). On 16.01.09, sampling was conducted under ice on lakes Fohnsee and Eishaussee. For sampling, a 2 L Ruttner water sampler (Hydrobios) was used. Groundwater was sampled for oxygen isotope analyses at a subaqueous ground water well close to the surface in Lake Waschsee on 4 occasions during the study period.

The oxygen isotopic ratio $R = {}^{18}O/{}^{16}O$ of the water samples was analysed at the Institute of Groundwater Ecology, Neuherberg, Germany with an isotope ratio mass spectrometer (Delta C, Finnigan MAT) following online-preparation by the CO_2-H_2O equilibration method (Moser & Rauert 1980). Presented values are the arithmetic mean of two independent measurements of the same sample, with the analytical precision (standard deviation of the mean) being always <0.1‰, in more than 70% of measurements even better than 0.05‰. They are reported as per mill in the delta notation against the international reference standard VSMOW (Vienna Standard Mean Ocean Water), where $\delta^{18}O_{sample} = (R_{sample}/R_{standard}{}^{-1}) \times 1000$.

Weather data were obtained from the weather station in Rothenfeld 21 km away (www.lfl.de/agm/).

2.3. Calculation of stability and statistical analysis

To account for the intensity of summer stratification, stability S *sensu* Schmidt as presented by Kjensmo (1994) was calculated for the whole water column of each lake for each sampling from March 2008 to April 2009. The density of water at each depth was calculated according to Chen & Millero (1986), conductivity was converted to salinity according to Boehrer & Schultze (2009).

Lake volume and area data were taken from a digital elevation model of all lakes produced by a sonar depth survey. They were also used to calculate volume-weighted means of the isotopic signature of all water layers of a lake at certain dates. A two-tailed *t*-test was used to test the permanence of isolation of bottom waters (16 m to bottom) in Lake Eishaussee. In addition, a linear regression was conducted to analyse a trend to lower values during stratification (21.05.08-18.11.08) in the hypolimnion of Lake Fohnsee (10-22 m). All figures and calculations were done either with the free statistic software *R* (www.r project.org) or with MS Excel 2003.

3. RESULTS

3.1. Local weather

Figure 2a-c shows the development of the main climatic parameters air temperature [°C], daily mean of wind speed [m s^{-1}] and daily sum of solar radiation [W m^{-2}] in the area of the study site for the period of March 2008 to April 2009.

Most noticeable was the occurrence of several rather short periods with a drop in air temperature and also solar radiation, combined with high wind velocities, especially at the beginning of March, July, and August 2008 and between 18.11.08 and 26.11.08.

3.2. Development of water temperature and Schmidt stability

The progression of lake water temperatures from March 2008 to April 2009 is depicted in figure 3a, c, e, and the calculated Schmidt stability S values in figure 4.

In Lake Waschsee, summer water warming was considerably dampened and visible over the whole depth, which resulted in very low Schmidt stability values (max. 11.3 g cm cm^{-2}).

In the middle of the summer stratification period lakes Fohnsee and Eishaussee showed an episode of considerable cooling (26.06.08 - 18.07.08) in the course of which surface waters to a depth of 4 m became isothermal. This resulted in a significant drop of the stability reached earlier (up to 25% in Lake Fohnsee). After this clear break the upper water layers were again subjected to substantial warming in late summer (07.08.08) and therefore exhibited high stability values (Lake Fohnsee: 502 g cm cm^{-2}). The end of the thermal stratification and the slow erosion of the epilimnion set in after 07.08.08 with the autumnal cooling of the lakes, which resulted in a continuous decline of Schmidt stability. Successive cooling led to a downward extension of the isothermal zone visible in the following samplings, so that on 26.11.08 after a strong storm event all lakes were in an isothermal state. About one week later, the formation of ice set in on lakes Fohnsee and Eishaussee and rendered them continuously covered with ice until the middle of March 2009.

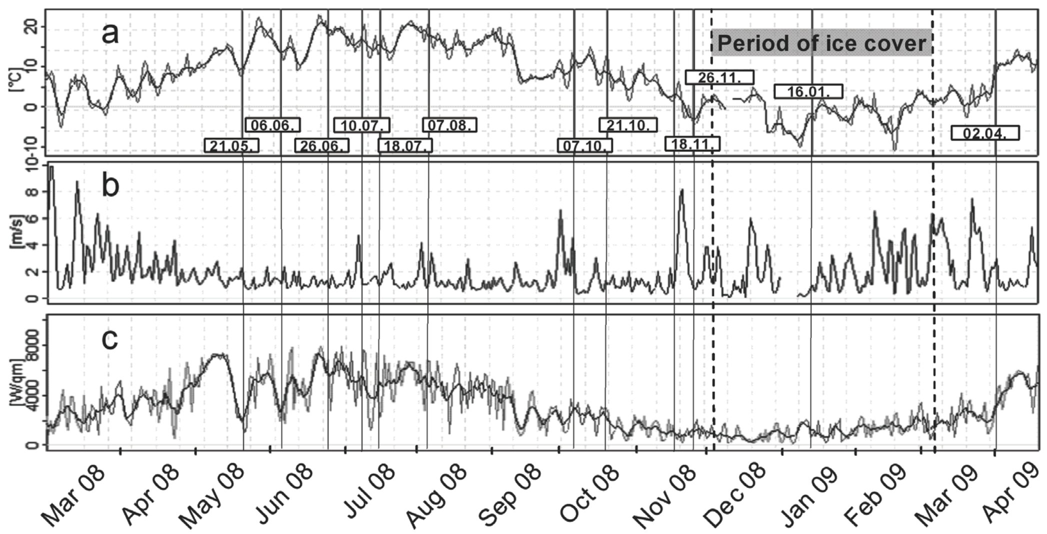

Fig. 2. weather data in the study area for the investigated period from March 2008 to April 2009. **a**: daily mean of air temperature [°C] (thin line) with the 5d running mean (bold line); **b**: mean daily wind speed [m s^{-1}]; **c**: daily sum of solar radiation [W m^{-2}] (thin line) with the 5 d running mean (bold line). Water $\delta^{18}O$ samplings are indicated by vertical lines and the respective date.

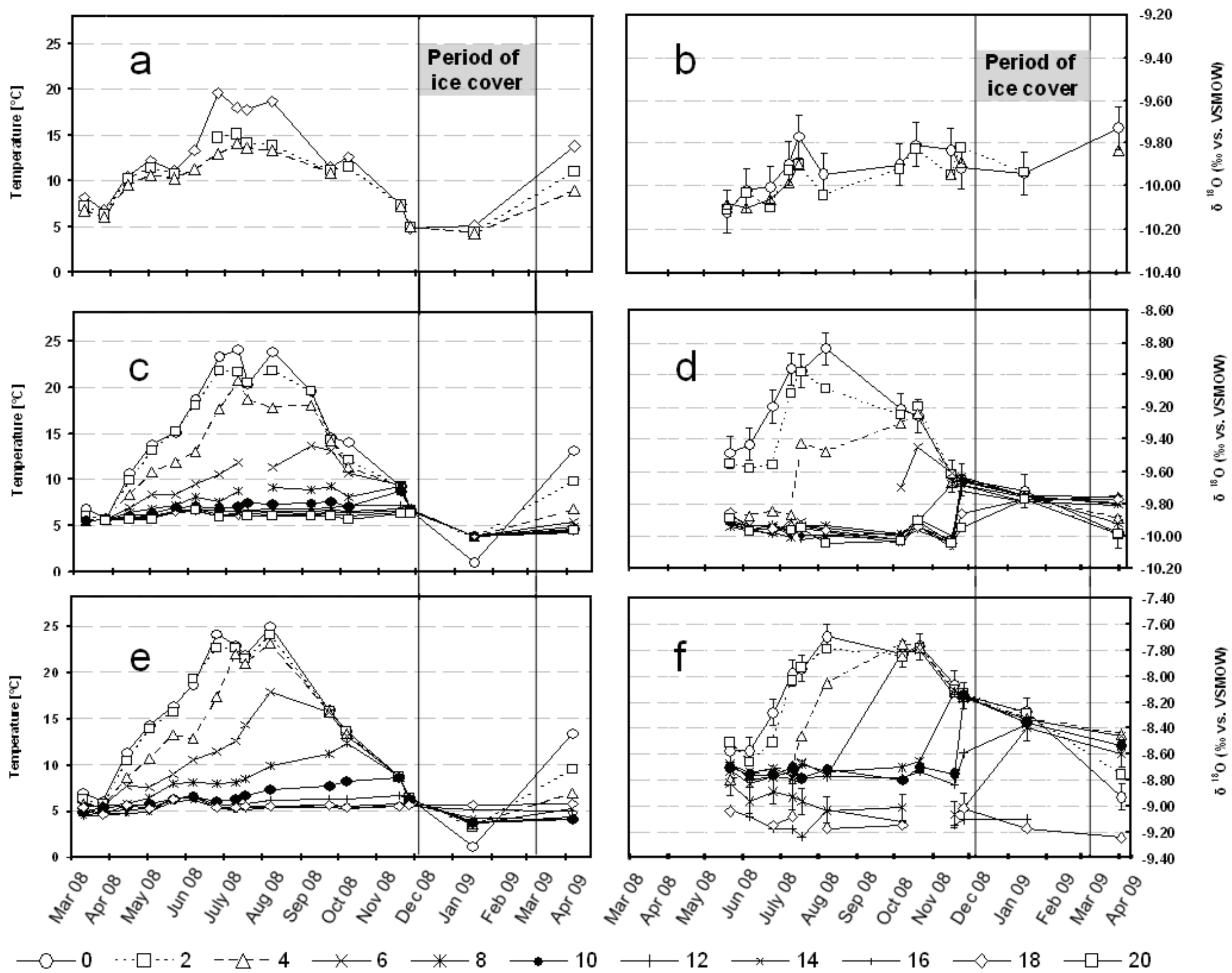

Fig. 3. Development of water temperature [°C] (left side) and oxygen isotopic signature $\delta^{18}O$ [‰] from March 2008 to April 2009 (right side) in the investigated lakes (**a**, **b**: L.Waschsee, **c**, **d**: L. Fohnsee, **e**, **f**: L. Eishaussee).

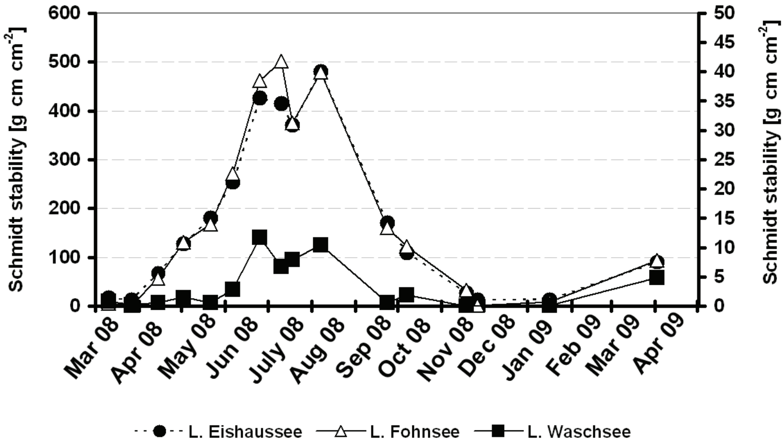

Fig. 4. Development of Schmidt stability [g cm cm^{-2}] from March 2008 to April 2009 in the investigated lakes. Note the different scales used for Lakes Fohnsee und Eishaussee (left) and L.Waschsee (right).

3.3. Development of ^{18}O isotopic signatures

The overall development of $\delta^{18}O$ in the water column was similar in lakes Fohnsee and Eishaussee (Fig. 3d, f). $\delta^{18}O$ of upper water layers steadily increased during summer months (May-August 2008) and returned to more depleted values in late autumn (August-November 2008). While in Lake Fohnsee this depletion led to a uniform isotope signal across the entire water column on 16.01.09, in Lake Eishaussee this homogenisation of $\delta^{18}O$ was constrained to a depth of 0-14 m. The bottom water layers (16-18 m) remained significantly (p <0.001) separated in signal from upper layers over the whole period of investigation.

In lakes Fohnsee and Eishaussee the influence of isotopic enrichment during summer was only visible in the topmost water layers (0-2 m), but began to extend to a depth of 4 m from 18.07.08 on. In autumn, a combination of two processes led to a uniform isotopic value in January 2009, being either restricted to parts of the water column (Eishaussee) or comprising all water layers (Fohnsee): first, a decline in signal extending from the water surface and secondly, several quite sudden increases of $\delta^{18}O$ in bottom water layers up to the current lake surface $\delta^{18}O$ value. Both absolute values of $\delta^{18}O$ and signal ranges proved to be different for the investigated lakes: in Lake Waschsee (Fig. 3b), the overall range of oxygen isotope signatures was rather narrow ($\Delta\delta^{18}O$ = 0.38‰) and the mean isotopic value ($\delta^{18}O$ = -9.94‰) of all water layers over the investigated period was closer to the signature of local groundwater ($\delta^{18}O$ = -10.01‰ ± 0.06‰) than the respective mean values of the other lakes. In Lake Waschsee isotopic differences between water layers were always below or close to analytical precision, although in the surface water layer a trend towards stronger isotopic enrichment and therefore a separation in signal from lower layers was apparent from 06.06.08 to 07.10.08. The respective mean isotopic values of the whole lake at the beginning (21.05.08) and at the end (02.04.09) of the sampling campaign were markedly different ($\delta^{18}O$ = -10.1‰ /-9.75‰).

This did not apply for lakes Fohnsee and Eishaussee (Fig. 3d, f), where differences between the mean isotopic values of the water column on the first (21.05.08) and the last (02.04.09) sampling were only minor ($\Delta\delta^{18}O$ = 0.11‰, 0.03‰). However, in the course of the study $\delta^{18}O$ values exhibited pronounced variation ($\Delta\delta^{18}O$ = 1.20‰, 1.23‰) and the mean isotope value of all water layers was higher ($\delta^{18}O$ = -9.66‰, -8.41‰) than in Lake Waschsee.

At the last sampling, conducted several days after ice melt, surface water layers to a depth of 4 m were characterised by lower oxygen isotopic values than the water layers below, although the difference ($\Delta\delta^{18}O$ = 0.16‰) was close to analytical precisition. This could also be seen in the surface layers (0-2 m) of Lake Eishaussee (0.32‰).

Interestingly, the hypolimnion (10-20 m depth) in Lake Fohnsee showed a highly significant trend (n = 47, r^2 = 0.65, p <0.001) towards lower oxygen isotope values from the beginning of the sampling campaign to the last day of stratification (21.05.08-18.11.08, without 21.10.08).

4. DISCUSSION

4.1. Local weather

The periods around 21.05.08 and 17.06.08 with a substantial drop in air temperature and solar radiation, but low wind speed affected the rising trend of water temperatures and stability only slightly.

In contrast to this, in July a period with comparatively small drops in air temperature and solar radiation had a strong effect on Schmidt stability, surface water temperature and isotopic signature. This is possibly due to the fact that after a long rather calm period a short event of strong wind occurred around 08.07.08, which is likely to have induced high shear velocities on the lakes surface, therefore enforcing the cooling of upper water layers and the deepening of the epilimnion, as seen in the isotopic signatures of the respective water layers. For Lake Eishaussee this might as well apply to the next wind event around 04.08.08, although in the meantime a considerable rise in air temperature occurred.

The autumnal cooling period began with a pronounced drop of air temperature in the middle of September (14.09.08) and was accompanied by two strong wind events (01.10.08/21.11.08), the latter coinciding with air temperatures below 0°C and followed by an isothermal situation in all three lakes.

4.2. Development of water temperature, stability and $\delta^{18}O$

4.2.1. Lake Waschsee

The relatively small observed range of both water temperature and δ^{18}O is a result of the very high water renewal rate, which is due to the low total volume and a strong subsurface inflow of groundwater with a uniform temperature of *ca* 9 °C (Melzer 1976). Besides the incomplete formation of an ice cover, the strength of this influence is also evident since the mean δ^{18}O signal of all water layers always remained closer to the signature of local groundwater than it was observed in the other lakes. The overall Schmidt stability was about 40 times lower than in lakes Fohnsee and Eishaussee and is in the same range as reported for other polymictic small lakes, e.g. Lake Marion near Vancouver BC, Canada, (11 g cm cm^{-2}) with a water renewal rate of approximately 76 times per year (Kjensmo 1994). The polymictic character of Lake Waschsee was more evident in the isotopic signature than in temperature profiles: While the surface (0 m) temperature showed considerable separation (up to 5 °C) from the remaining water body between 21.05.08-07.10.08, the isotopic signal of bottom water layers clearly followed the surface water δ^{18}O trend and isotopic differences between these layers were always minor.

Although seeming contradictory at first, this might be due to the fact that the surface water temperature usually reflects a daily pattern, while the isotope signal integrates over time. Near-surface thermoclines that form and disappear in a diurnal rhythm are a very common phenomenon in small, wind protected lakes (Imberger 1985; Xenopoulos & Schindler 2001). The pronounced differences in the mean δ^{18}O of Lake Waschsee at the beginning and end of the sampling campaign are consistent with the explanation presented by Gibson *et al*. (2002) that lakes of smaller volume and water residence time below one year are likely to show a seasonally fluctuating mean isotopic signature. Lakes of larger volume, higher water residence time and therefore a large buffer capacity for water δ^{18}O are expected to exhibit near-constant signals, as they were shown for lakes Fohnsee and Eishaussee.

4.2.2. Lake Fohnsee

As in the case of Lake Waschsee, in Lake Fohnsee the δ^{18}O signal was a better indicator of the state of isolation and mixis of water layers than their respective temperature. While during most of the early summer (26.03.08-06.06.08), the upper two water layers remained virtually indistinguishable in temperature, the isotopic signature in 2 m depth remained unaffected by the continuous enrichment in the topmost layer until 26.06.08. In the following, the drop in air temperature resulted in a cooling of surface waters and a corresponding drop in Schmidt stability, which increased the susceptibility for windinduced mixing. The storm event at 08.07.08 produced an erosion of the thermocline and a deepening of the epilimnion by entrainment as indicated by the sudden leaps of δ^{18}O. Visible in the stable δ^{18}O isotopic signature but not in the temperature profile, the effect of this entrainment had extended to the depth of 4 m at the following sampling.

Entrainment during the stratification period can be a determining factor for the intensity of primary production and algal blooms, as nutritions are released from the hypolimnion into the euphotic zone: Soranno *et al*. 1997 investigated the epilimnetic phosphorus budget of an North American eutrophic lake and found the amount of phosphorus transported to the epilimnion by entrainment to exceed external loading by an order of magnitude in one year.

The windy but warm period at the beginning of August did not affect the separation of the surface layers (0-2 m) as indicated by both δ^{18}O and temperature. The marked decrease of δ^{18}O originating from the surface layers in autumn and early winter is the result of a combination of several effects. First, the influence of evaporation enrichment was lifted; therefore the evaporation/inflow ratio decreased and the δ^{18}O signal of the inflow became more determining (Gibson *et al*. 2002). Secondly, precipitation (rainfall and surface runoff) typically displays lower isotope signatures and precipitation levels increase in autumn and winter compared to summer (Mook & Rozanski 2000). This is confirmed for the investigated area by the long term weighted means for δ^{18}O of precipitation in August (-7.96‰) and October (-12.35‰) at the nearest GNIP station of Hohenpeissenberg (http://nds121.iaea.org/wiser/).

The abrupt rises in δ^{18}O of single bottom water layers visible in autumn are likely due to stepwise entrainment of those layers and mixing with surface water. The isotopic signature revealed for Lake Fohnsee and the upper dimictic part of Lake Eishaussee that the isothermal state on 26.11.08 after a strong storm event did not coincide with a circulation of the whole water column. Full homogenisation of δ^{18}O was not visible until 16.01.09 when sampling was conducted under ice. This implicates further mixing either prior to or after the formation of ice. The latter is supported by additional evidence, as the sampling under ice did not reveal a different isotopic signature of the surface water layer, as would otherwise be expected. During the formation of ice out of liquid water preferentially heavy isotopes are incorporated into the solid state (Friedman & Redfield 1957 cit. in Tyler *et al*. 2007). Therefore the surface water directly beneath the ice is expected to be, at least to some degree, depleted of heavy isotopes compared to the remaining water column. This effect has been shown to be significant for $\delta^{18}O$ even in the whole water column of antarctic and alpine lakes (Krabbenhoft *et al*. 1990; Gibson *et al*. 2002). Some disturbance of water layering might have been induced during the removal of the ice for sampling. However, we suggest that the absence of a different surface water $\delta^{18}O$ and the clear trend towards more depleted isotopic signatures visible in all water layers of Lake Fohnsee and the mixolimnion of Lake Eishaussee are a sign of ongoing mixing processes under the ice layer. This phenomenon was also frequently reported for ice covered lakes by other authors (Farmer 1975; Bengtsson 1996; Petrov *et al*. 2007).

At the last sampling on 06.04.09 the onset of snow and ice melt was clearly reflected by depleted ^{18}O surface water signals (cf. Mook & Rozanski 2000). Accordingly, the significantly lower isotope signature of the bottom water layer (20 m) at this sampling ($\delta^{18}O$ = -9.98‰) might be due to the influence of melt water sinking to the bottom of the lake as described by Tyler *et al*. (2007) for a small Scottish lake. However, the reason for this remains unclear, as the almost uniform temperature of bottom waters was close to the point of maximum density.

The highly significant trend towards more depleted oxygen isotope values which was visible in the bottom water layers of Lake Fohnsee indicates considerable groundwater inflow during the study period, as the isotopic signature of water can only be changed via significant mass transport (Dincer 1968). This is an important finding, because until now, Lake Fohnsee had not been considered receiving significant groundwater inflow (Melzer 1976). Since we are not able to give a concise explanation for the rise of $\delta^{18}O$ visible in all bottom water layers of Lake Fohnsee on 21.10.08, the isotopic results of this sampling were not used in the calculation of the regression.

4.2.3. Lake Eishaussee

Under given climatic conditions, the mean oxygen isotopic composition of a lake is determined only by the long term means of both the isotopic composition of the inflow and the ratio of inflow/evaporation (Dincer 1968, Gibson *et al*. 2002). Lake Eishaussee is considered not to be influenced by groundwater (Melzer 1976) and receives its inflow from surface water layers of the neighbouring lakes. This permits a considerable isotopic enrichment of its inflow compared to the original groundwater by the "string-of-lakes" effect as described by Gat & Bowser (1991). However, one of the lakes connected to Lake Eishaussee is Lake Fohnsee with a mean isotopic signature quite close to $\delta^{18}O$ of local groundwater. Therefore we propose that the relatively depleted mean oxygen isotopic signal found in Lake Eishaussee is the result of a water residence time significantly higher than in Lake Fohnsee, as both are subjected to the same climatic conditions. In Lake Fohnsee, the possible effect of isotopic enrichment by evaporation is likely to be attenuated by dilution (Gibson *et al*. 1996) due to a higher water renewal rate and inflow of isotopically depleted groundwater.

The permanent meromictic situation of Lake Eishaussee was was clearly reflected by the continuous separation in $\delta^{18}O$ of the monimolimnion (16 m, 18 m) from the mixolimnion during the whole study period. The oldest published record mentioning this condition of Lake Eishaussee (Zorell 1941) allows the conclusion that the lake has been meromictic for the last 70 years. Recent sediment investigations in Lake Eishaussee indicate that it has been meromictic for much longer (Braig, to be published). The sampling under ice on 16.01.08 revealed a full circulation of water layers from 0-14 m depth, which was not present at the sampling at isothermal conditions before. Thus, the $\delta^{18}O$ signal indicates that the boundary between mixolimnion and monimolimnion is somewhere between 14 m and 16 m depth, which is confirmed from conductance depth profiles (data not shown).

The location of Lake Eishaussee is protected against wind influences considerably more than that of the other investigated lakes. While this condition may have helped in the conservation of the present meromictic situation, it was noticeable to a small amount in the isotopic signature of the surface water layers (0-2 m): They repeatedly showed different oxygen isotopic signatures over the summer, although this effect was almost always below analytical precision.

5. CONCLUSIONS

The extent of stratification and mixis especially during the summer stratification is a determining aspect for the vast majority of lakes in temperate regions of low to mid altitude, as it is bound to have important effects on nearly all biological, chemical and physical processes, particularly on the trophic state and primary production. However, though being crucial, the occurrence of mixing events in the water column is not always easily detected by standard measurements.

The present study of $\delta^{18}O$ in the water column of three lakes with very different hydrology proved the high suitability of the stable oxygen isotopic signature of water for the routine investigation of important mixis and stratification processes in lakes.

The presented findings confirm important implications for lake water balance investigations that use the degree of isotopic enrichment in a water body to account for the influence of evaporation compared to inflow (Gibson *et al*. 1996; Mayr *et al*. 2007; Yi *et al*. 2008). As already pointed out by Gibson *et al*. (2002), the influence of evaporation is easily overestimated when the assumption of an isotopically well mixed reservoir is not valid and a stronger enrichment is found in the sampled topmost water layers. Depending on the desired level of precision, sampling should thus cover the whole water column with suitable temporal resolution to account for such influences.

This should also be considered an important implication for paleoclimatic studies that use the oxygen or hydrogen isotopic signal of authigenic or biogenic components (e.g., diatoms, chironomids, authigenic and biogenic carbonates) produced in certain depths and seasons, to reconstruct past lake water $\delta^{18}O$ (e.g., Wooller *et al*. 2004; Leng & Barker 2006; Wolfe *et al*. 2007). The input functions for these materials need to be carefully defined, as the seasonal and spatial variations revealed by our study are likely to induce considerable non-systematic error to such reconstructions of lake water $\delta^{18}O$.

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REFERENCES

Ambrosetti, W., L. Barbanti & E. Carrara. 2001. Mechanisms of hypolimnion erosion in a deep lake (Lago Maggiore, N. Italy). *J. Limnol.* 69(1): 1-12.

Barbiero, R.P., W.F. James & J.W. Barko. 1997. The effects of a change in withdrawal operations on phytoplankton and nutrient dynamics in Eau Galle Reservoir, Wisconsin (USA). *Int. Revue ges. Hydrobiol.*, 82(4): 531-543.

Bengtsson, L. 1996. Mixing in ice-covered lakes. *Hydrobiologia*, 322(1): 91-97.

Boehrer, B. & M. Schultze. 2009. *Density Stratification and Stability. Encyclopedia of Inland Waters*. G.E. Likens, Oxford: Elsevier. 1: 583-593.

Caliro, S., G. Chiodini, G. Izzo, C. Minopoli, A. Signorini, R. Avino & D. Granieri. 2008. Geochemical and biochemical evidence of lake circulation and fish kill at Lake Averno, Italy. *Journal fo Volcanology and Geothermal Research*, 178(2): 305-316.

Carstensen, J., D.J. Conley & P. Henriksen. 2004. Frequency, composition, and causes of summer phytoplankton blooms in a shallow coastal ecosystem, the Kattegat. *Limnol. Oceanogr.*, 49(1): 191-201.

Chen, C. & F. Millero. 1986. Precise thermodynamic properties for natural waters covering only the limnological range. *Limnol. Oceanogr.*, 31(3): 657-662.

Craig, H. 1961. Isotopic variations in meteoric waters. *Science*, 133(3465): 1702-1703.

Delalande, M., L. Bergonzini, F. Beal, Y. Garcin, A. Majule & D. Williamson. 2005. Contribution to the detection of Lake Masoko (Tanzania) groundwater outflow: isotopic evidence (18 O, D)/Contribution à la détection des pertes souterraines du Lac Masoko (Tanzanie): évidences isotopiques (18 O, D). *Hydrol. Sci. J.*, 50(5): 867-880.

Dincer, T. 1968. The use of oxygen-18 and deuterium concentrations in the water balance of lakes. *Water Resour. Res.*, 4(6): 1289-1306.

Farmer, D.M. 1975. Penetrative convection in the absence of mean shear. *Quart. J. Royal Meteor. Soc.*, 101: 869-891.

Gat, J. & C. Bowser. 1991. The heavy isotope enrichment of water in coupled evaporative systems. Stable Isotope Geochemistry: a Tribute to Samuel Epstein: 159-168.

Gat, J. 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. *Annu. Rev. Earth Pl. Sc.*, 24(1): 225-262.

Gibson, J., T. Edwards & T. Prowse. 1996. Development and validation of an isotopic method for estimating lake evaporation. *Hydrol. Process.*, 10(10): 1369-1382.

Gibson, J., E. Prepas & P. McEachern. 2002. Quantitative comparison of lake throughflow, residency, and catchment runoff using stable isotopes: modelling and results from a regional survey of Boreal lakes. *J. Hydrol.*, 262(1-4): 128-144.

Gibson, J., T. Edwards, S. Birks, N. St Amour, W. Buhay, P. McEachern, B. Wolfe & D. Peters. 2005. Progress in isotope tracer hydrology in Canada. *Hydrol. Process.*, 19(1): 303-327.

Gupta, S. & R. Deshpande. 2004. An insight into the dynamics of Lake Nainital (Kumaun Himalaya, India) using stable isotope data. *Hydrol. Sci. J.*, 49(6): 1099-1114.

Hofmann, H., K. Knoller & D. Lessmann. 2008. Mining lakes as groundwater-dominated hydrological systems: assessment of the water balance of Mining Lake Plessa 117 (Lusatia, Germany) using stable isotopes. *Hydrol. Process.*, 22(23): 4620-4627.

Holzner, C., W. Aeschbach-Hertig, M. Simona, M. Veronesi, D. Imboden & R. Kipfer. 2009. Exceptional mixing events in meromictic Lake Lugano (Switzerland/Italy), studied using environmental tracers. *Limnol. Oceanogr.*, 54: 1113-1124.

Hostetler, S. & L. Benson. 1994. Stable Isotopes of Oxygen and Hydrogen in the Truckee River-Pyramid Lake Surface-Water System. 2. A Predictive Model of $\delta^{18}O$ and $\delta^{2}H$ in Pyramid Lake. *Limnol. Oceanogr.*: 356-364.

Imberger, J. 1985. The diurnal mixed layer. *Limnol. Oceanogr.*: 737-770.

Kjensmo, J. 1994. Internal energy, the work of the wind, and the thermal stability in Lake Tyrifjord, southeastern Norway. *Hydrobiologia*, 286(1): 53-59.

Krabbenhoft, D.P., C.J. Bowser, M.P. Anderson & J.W. Valley. 1990. Estimating groundwater exchange with lakes 1. The stable isotope mass balance method. *Water Resour. Res.*, 26(10): 2445-2453.

Leng, M.J. & P.A. Barker. 2006. A review of the oxygen isotope composition of lacustrine diatom silica for palaeoclimate reconstruction. *Earth Sci. Rev.*, 75(1-4): 5-27.

MacIntyre, S. 1993. Vertical mixing in a shallow, eutrophic lake: Possible consequences for the light climate of phytoplankton. *Limnol. Oceanogr.*, 38(4): 798-817.

Mayr, C., A. Lücke, W. Stichler, P. Trimborn, B. Ercolano, G. Oliva, C. Ohlendorf, J. Soto, M. Fey & T. Haberzettl. 2007. Precipitation origin and evaporation of lakes in semi-arid Patagonia (Argentina) inferred from stable isotopes (^{18}O, ^{2}H). *J. Hydrol.* 334(1-2): 53-63.

Melzer, A. 1976. Makrophytische Wasserpflanzen als Indikatoren des Gewässerzustandes oberbayerischer Seen. *Dissertationes Botanicae*; 34; 1-195. Vaduz, J.Cramer: 195.

Mook, W.G. & K. Rozanski. 2000. *Environmental isotopes in the hydrological cycle*. IAEA Publish, Vienna: 280 pp.

Moser, H. & W. Rauert. 1980. *Isotopenmethoden in der Hydrologie*. Borntraeger, Berlin: 400 pp.
Perini, M., F. Camin, F. Corradini, U. Obertegger & G. Flaim. 2009. Use of ^{18}O in the interpretation of hydrological dynamics in lakes. *J. Limnol*., 68(2): 174-182.
Petrov, M.P., A.Y. Terzhevik, R.E. Zdorovennov & G.E. Zdorovennova. 2007. Motion of water in an ice-covered shallow lake. *Water Resour*., 34(2): 113-122.
Rothpletz, A. 1917. *Die Osterseen und der Isar-Vorlandgletscher*. Mitt. Geogr. Ges. München, 12: 1-314.
Salmaso, N. 2005. Effects of climatic fluctuations and vertical mixing on the interannual trophic variability of Lake Garda, Italy. *Limnol. Oceanogr*., 50(2): 553-565.
Schmidt, W. 1928. Über Temperatur und Stabilitätsverhältnisse von Seen. *Geogr. Ann*., 10: 145-177.
Soranno, P.A., S.R. Carpenter & R.C. Lathrop. 1997. Internal phosphorus loading in Lake Mendota: response to external loads and weather. *Can. J. Fish Aquat. Sci*., 54(8): 1883-1893.
Stichler, W., P. Maloszewski, B. Bertleff & R. Watzel. 2008. Use of environmental isotopes to define the capture zone of a drinking water supply situated near a dredge lake. *J. Hydrol*., 362(3-4): 220-233.

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Tyler, J.J., M.J. Leng & C. Arrowsmith. 2007. Seasonality and the isotope hydrology of Lochnagar, a Scottish mountain lake: implications for palaeoclimate research. *The Holocene*, 17(6): 717.
Wetzel, R.G. 2001. *Limnology - Lake and River Ecosystems*. Academic Press, New York: 1006 pp.
Wolfe, B.B., M.D. Falcone, K.P. Clogg-Wright, C.L. Mongeon, Y.Yi, B.E. Brock, N.A.S. Amour, W.A. Mark & T.W.D. Edwards. 2007. Progress in isotope paleohydrology using lake sediment cellulose. *J. Paleolimnol*., 37(2): 221-231.
Wooller, M.J., D. Francis, M.L. Fogel, G.H. Miller, I.R. Walker & A.P. Wolfe. 2004. Quantitative paleotemperature estimates from δ^{18}O of chironomid head capsules preserved in arctic lake sediments. *J. Paleolimnol*., 31(3): 267-274.
Xenopoulos, M. & D. Schindler. 2001. The environmental control of near-surface thermoclines in boreal lakes. *Ecosystems*, 4(7): 699-707.
Yi, Y., B. Brock, M. Falcone, B. Wolfe & T. Edwards. 2008. A coupled isotope tracer method to characterize input water to lakes. *J. Hydrol*., 350(1-2): 1-13.
Zorell, F. 1941. Beiträge zur Kenntnis der oberbayrischen Osterseen. *Mitt. Geogr. Ges*. *München*, 33: 19-43.