Density-driven exchange between the basins of Lake Lucerne (Switzerland) traced with the $^3$H-$^3$He method

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Abstract

Lake Lucerne is divided by sills into four major and two minor basins. During winter, differential vertical mixing due to non-uniform wind exposure and different total dissolved solid concentrations in the main tributaries of the lake cause considerable interbasin density gradients. These gradients induce density-driven currents across the sills that contribute significantly to the deep water exchange in the basins and gradually reduce the density gradients during summer.

Over a period of 2 yr (1990-1992), the spatial and temporal evolution of water density and water age (measured by the $^3$H-$^3$He method) was investigated. Variation in water age between the different basins and the occasional occurrence of age inversions (older water overlying younger one) can be explained in terms of the observed density distribution and the exchange flows the density gradients cause. Water age provides an integral measure of the magnitude of deep-water renewal, which in some basins can be roughly separated into contributions from density-driven currents and wind-induced vertical mixing.

By correlating water age with dissolved helium and oxygen concentrations, radiogenic helium fluxes and average oxygen depletion rates were determined for the main basins of the lake. The helium flux was between 1 and $2 \times 10^{10}$ atoms m$^{-2}$ s$^{-1}$, indicating dynamic equilibrium with helium production in the underlying crust. Oxygen depletion rates per unit sediment area were roughly equal in all basins (between 220 and 290 g m$^{-2}$ yr$^{-1}$), whereas volumetric depletion rates varied from 1.8 g m$^{-3}$ yr$^{-1}$ in the deepest basin to 10 g m$^{-3}$ yr$^{-1}$ in the shallowest.

Acknowledgments

This study could not have been done without the help of many people, among whom we mention especially Captain Mike Schurter and technicians Urs Menet and Stefan Thiirig. Johny Wiiest contributed his knowledge of Lake Lucerne to the planning of the field program. Peter Signer's critical comments were helpful for both experimental work and the writing. Roland Hohmann worked on the lake as well as in the laboratory. Two anonymous reviewers provided constructive comments.

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Currents driven by horizontal density differences, in particular exchange currents over sills, have been extensively studied in the ocean, both theoretically and experimentally (e.g. Chao and Paluszskiewicz 1991; Farmer and Armi 1986). Well-known examples are the exchange between the Mediterranean Sea and the Atlantic Ocean through the Strait of Gibraltar (e.g. Tziperman 1987) or the overflow of Arctic-type waters through the Denmark Strait into the North Atlantic (e.g. Dickson et al. 1990).

Density currents in lakes have attracted less attention. Small and simple-shaped lakes often have rather small and short-lived horizontal density gradients. However, density-driven flow may be important in larger lakes that have distinct topographic features such as shallow embayments, sill-separated basins, or basins with different wind exposures. The effect of a shallow, sheltered bay on mixing in the whole lake has been studied by Imberger and Parker (1985) in Wellington Reservoir (Australia). Examples for sill-separated basins are the Überlingserssee/Obersee pair in Lake Constance (Bodensee—Germany/Switzerland/Austria) (Zenger et al. 1990), and the Gersauerssee/Urnersee system in Lake Lucerne (also known as Vierwaldsätterssee, see Fig. 1).

Wüest et al. (1988) were the first to postulate the existence of a density-driven current from Gersauerssee into the deep layers of Urnersee (i.e. against the main flow direction in the lake). During May and June 1986, they were able to quantify a mean flow of $10 \times 10^6$ m$^3$ d$^{-1}$ based on temperature and conductivity data, which replaced 65% of the water mass below 110 m in Urnersee. van Senden and Imboden (1989) showed that internal seiches in Gersauerssee can pump water from deeper layers in Gersau Basin over a sill into the intermediate Treib Basin (Fig. 1) and eventually into Urnersee. They estimated that the water exchange by seiche pumping is by an order of magnitude smaller than the continuous density flow.

On the basis of historical data records from the years 1965-1974, van Senden et al. (1990) showed that the density current postulated by Wüest et al. (1988) is a regular phenomenon in spring. van Senden et al. showed that the temperature and conductivity characteristics of the deep hypolimnion of Urnersee can be interpreted as...
a mixture of water from intermediate depths of Gersauersee and Umersee, respectively. A direct proof for the existence of a density current into Umersee was presented by Schlatter (1991). In spring 1989, SF$_6$ was added to the deep water of Treib Basin from whence it penetrated into the deepest layers of Umersee within a few days. The experiment confirmed the magnitude of the exchange calculated by Wüest et al. (1988).

The rather complex mixing behavior of Lake Lucerne is not restricted to the Umersee/Gersauersee boundary. The lake consists of four main and two intermediate basins, each of which exhibits its individual physical-chemical properties. Our study examines the lake as an example of the subtlety of the three-dimensional physics of freshwater lakes. Our goal is to discuss and quantify the contribution of density-driven currents to the exchange of water between the basins, to vertical mixing, and to the formation of deep water in each basin. The consequences of the complex mixing pattern for chemical and biological processes (e.g. for the spatial distribution of dissolved oxygen) are discussed.

Precise measurement of temperature and electrical conductivity (salinity) is indispensable to understanding the mechanisms governing the exchange of water. Because freshwater has a density maximum at 4°C (at surface pressure) where the thermal expansion coefficient is zero, even a small difference in electrical conductivity can have a decisive influence on water density. In addition, temperature and electrical conductivity can in some cases be used as tracers for the intrusion of water from rivers or between adjacent basins.

Most physical-chemical processes in lakes occur over much shorter time scales than in the ocean. Thus, the choice of adequate natural tracers for the study of mixing is rather limited. Chlorofluorocarbons (CFCs) were used by Weiss et al. (1991) to study mixing times of 10 yr in Lake Baikal (Siberia), but their applicability to lakes with turnover times of months to a few years remains to be demonstrated. Such demonstration was provided by Torgersen et al. (1977) and others for the tritium-helium ($^3$H-$^3$He) tracer pair.

In this study, the $^3$H-$^3$He water mass age serves to quantify deep-water renewal in the individual basins of Lake Lucerne. In addition, age is used to trace water exchange between the basins, and its temporal and spatial variation confirms the existence of density-driven currents that have been indirectly deduced from the spatial distribution of water density.

Geography, morphology, and limnology of Lake Lucerne

Lake Lucerne has an irregular horizontal shape (Fig. 1A) matched by a complicated bottom topography that includes several sills (Fig. 1B). These sills define four main basins, two of which can be further divided into subbasins separated by less distinct sills. Some physical properties of the lake and its basins are summarized in Table 1.

Our discussion is largely based on tracer distributions along the longitudinal section shown in Fig. 1B. Following the course of the Reuss, the main tributary river, the section cuts through Umersee, Gersauersee (consisting of the Treib and Gersauer Basins), and Vitznauersee (divided into Obermatt Basin and the Big Cross Funnel). The section then turns toward the small and shallow Alpnachersee, which is connected to the main body of the lake by a shallow channel. Alpnachersee can be viewed as an upstream lake that experiences little or no feedback from the main water body but has, as will be shown, an important influence on the dynamics of the main lake.

In the 1960s, the naturally oligotrophic lake showed signs of becoming mesotrophic (Ambüh 1969). Measures to reduce the input of phosphorus were taken quickly and triggered a surprisingly fast recovery (Ambüh 1987). Today, the lake is again oligotrophic. The higher nutrient
Table 1. Physical properties of Lake Lucerne (47°N, 8.5°E, 434 m asl).

<table>
<thead>
<tr>
<th>Property</th>
<th>AL</th>
<th>CF</th>
<th>OM</th>
<th>GE</th>
<th>TR</th>
<th>UR</th>
<th>Whole lake</th>
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<tr>
<td>Surface (km²)</td>
<td>4.76</td>
<td>35.0</td>
<td>22.0</td>
<td>25.4</td>
<td>4.83</td>
<td>22.0</td>
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<tr>
<td>Volume (10⁶ m³)</td>
<td>104</td>
<td>1,980</td>
<td>2,310</td>
<td>4,000</td>
<td>421</td>
<td>3,170</td>
<td>11,990</td>
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<tr>
<td>Max depth (m)</td>
<td>35</td>
<td>112</td>
<td>151</td>
<td>214</td>
<td>125</td>
<td>200</td>
<td>214</td>
</tr>
<tr>
<td>Depth below sill (m)</td>
<td>30</td>
<td>12</td>
<td>51</td>
<td>129</td>
<td>32</td>
<td>107</td>
<td>-</td>
</tr>
<tr>
<td>Mean discharge (m³ s⁻¹)</td>
<td>12</td>
<td>109</td>
<td>91</td>
<td>88</td>
<td>70</td>
<td>50</td>
<td>109</td>
</tr>
<tr>
<td>Residence time (yr)</td>
<td>0.27</td>
<td>0.38</td>
<td>0.80</td>
<td>1.44</td>
<td>0.19</td>
<td>2.01</td>
<td>3.49</td>
</tr>
</tbody>
</table>

*Basins identified in Fig. 1B.
†Data from an unpublished compilation of H. Bührer.
‡Depths of the isolated parts of the basins below the sills, estimated based on topographic maps.
§Estimated based on long-term mean runoff of the major tributaries from Swiss hydrological yearbooks.
∥Theoretical hydrological residence time, calculated as volume divided by net discharge.

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Concentrations in the past did not affect all the basins in the same way. For instance, between 1965 and 1974 the O₂ concentrations in the deep part of Gersauersee dropped to very low values but remained close to saturation at the bottom of Urnersee (van Senden et al. 1990). Because nutrient concentrations in the two basins have always been similar, other factors must have been important for the different behavior of the two basins. Such observations were part of the motivation to look more closely into the physics of the lake.

The physical processes in the lake are closely related to the rather inhomogeneous external forcing imposed by wind and rivers. The strongest wind is the Föhnl, a warm and dry wind that blows across the Alps from the south. When the Föhnl is strong, wind speeds >10 m s⁻¹ occur on Urnersee. Because these storms are especially frequent in spring, when thermal stratification is weak, they can induce strong vertical mixing and heat transport into the deep water of Urnersee (Wüest et al. 1988). Unlike Urnersee, Gersauersee and Obermatt Basin are sheltered from south winds by high mountains and therefore experience less efficient vertical mixing. The Big Cross Funnel is more exposed to winds from all directions, causing larger mixed-layer depths compared to the adjacent Obermatt Basin (Ambühl 1969). The shallow Alpnachersee is the only basin of Lake Lucerne that is completely mixed every winter and cools to 4°C and less.

Unlike Alpnachersee because backflow of water from the main lake is hindered by topography.

Altogether, the forcing by wind and rivers produces light (warm and fresh) water in Urnersee, on one end of the lake, and heavy (cold and salty) water in Alpnachsee, on the other end. As a consequence, a horizontal density gradient builds up along the whole lake.

Methods and materials

Sampling and measurement—During the period of April 1990 to November 1992, extensive CTD (conductivity, temperature, depth) profiles were taken on 12 expeditions. Most of the sampling stations shown in Fig. 1 were usually visited. Special emphasis was put on measurements in winter and early spring, when horizontal density gradients are most pronounced. In most cases, dissolved oxygen was measured by a sensor attached to the CTD probe.

Along with the CTD measurements, several water samples for ³H-³He were taken. Because the analysis of these isotopes requires a comparatively large effort, time and location for these samples were carefully chosen based on two objectives. First, to quantify vertical mixing in the individual basins; to this end, sampling stations in the deepest part of each basin were chosen (stations shown bold face in Fig. 1). Second, to look for possible imprints of density currents on the distribution of ³H and ³He; to this end, in early spring (March-April), when density currents were supposed to operate, or in fall (November), toward the end of the summer stratification, samples were taken from stations in the vicinity of the sills. The most comprehensive sampling was performed in April 1991 (50 samples). During this time, two current meters were moored on top of the sill between Gersauersee and the Obermatt Basin.

The CTD probe we used (Meerestechnik-Elektronik GmbH) has a resolution of 0.002 K for temperature and
0.2 μS cm⁻¹ for conductivity and a sampling rate of 0.5 s⁻¹. Normalization of the measured conductivities to 20°C as well as calculation of water density from temperature and normalized conductivity were done with slight modifications of the empirical equations of Bühler and Ambühl (1975) as given by von Senden et al. (1990). The derivation of the relationship between conductivity and density for the specific ion composition of a given lake is discussed in more detail by Wüst et al. (1996). The oxygen sensor (a Clarke electrode) has a response time of ~10 s and is subject to drift. Hence, regular calibrations against samples measured with the usual Winkler titration method were performed. Measurements of current velocity were performed by means of acoustic current meters (Neil Brown) with a resolution of 2 mm s⁻¹. Due to a zero point drift, the absolute accuracy is only ±1 cm s⁻¹ as long as no independent zero point calibration can be made.

Water samples were collected with 5-liter Niskin samplers. The water was transferred through a short piece of a soft rubber hose into either a copper tube for ³H-³He analysis or into a glass flask for Winkler titration. Helium, neon, and tritium (via its decay product ³He) were measured by mass spectrometry. Except for some modifications, we followed the methods described by Clarke et al. (1976) and Bayer et al. (1989). The copper tubes containing the water samples were directly connected to a vacuum line in order to extract and separate the dissolved helium and neon fractions, which were then measured simultaneously in different, noncommercial mass spectrometers. To check the reproducibility of the whole extraction and preparation procedure, we analyzed aliquots of a freshwater standard from time to time. The currently achieved long-term mean reproducibility is 0.5% for the ³He : ⁴He ratio, 0.6% for ⁴He amounts, and 0.7% for Ne amounts (1σ errors), but the measurement of the absolute gas amounts in some of the early samples was slightly less precise.

As a peculiarity of our procedure, the water is transferred back into the original copper tube after degassing for the He-Ne analysis. Usually, the sample is degassed again after 3 to 4 months to measure the newly produced ³He. The tritium concentration calculated from the regrown ³He has an error of ~3%. More details concerning the noble gas analysis are given by Kipfer et al. (1994) and Aeschbach-Hertig et al. (1996).

Calculation of ³H-³He water mass ages—The ³H-³He water mass age τ is calculated from the basic equation (e.g. Torgersen et al. 1977)

\[ \tau = \frac{1}{\lambda} \ln \left( 1 + \frac{[^{3}\text{He}_{\text{tri}}]}{[^{3}\text{H}]} \right) \]

(1)

\[ \lambda = 0.05576 \text{ yr}^{-1} \] is the decay constant of tritium (Utermöhrer et al. 1980), and [³H] and [³Heₗₘ] are the measured concentrations of tritium and tritiogenic ³He. The former concentration is usually given in TU (tritium units, 1 TU is equivalent to a ³H : ¹H ratio of 10⁻¹⁸), the latter in cm³STP g⁻¹ (cm³ gas at standard temperature and pressure per gram of water). Note that 1 cm³STP g⁻¹ = 4.019 x 10¹⁴ TU. If [³Heₗₘ] / [³H] is small compared to one (i.e. if \( \tau \ll 1/\lambda \)), Eq. 1 can be linearized to give

\[ \tau = \frac{1}{\lambda} \ln \left( \frac{[^{3}\text{He}_{\text{tri}}]}{[^{3}\text{H}]} \right) \]

(2)

The main problem in calculating ³H-³He ages is to accurately distinguish between tritiogenic and other ³He. In the simplest case, only tritiogenic ³He and He at atmospheric equilibrium are present in the water. The neon concentration can be used to check for the atmospheric equilibrium hypothesis. The amount of tritiogenic ³He in a given sample is then calculated as

\[ ^{3}\text{He}_{\text{tri}} = ^{4}\text{He}_{\text{m}} (R_{\text{m}} - R_{\text{eq}}) \]

(3)

³Heₗₘ is the measured helium amount, Rᵐ is the measured ³He : ⁴He ratio, and Rₑ is the ³He : ⁴He ratio in water in equilibrium with the atmosphere. Rₑ has been precisely determined by Benson and Krause (1980). For freshwater in the usual temperature range, Rₑ is ~1.7% smaller than the atmospheric ratio, \( R_{\text{a}} = 1.384 \times 10^{-6} \) (Clarke et al. 1976). For tritium concentrations of 30 TU, as presently measured in Lake Lucerne, the Rₑ error of 0.5% leads to an error in the water age of ~1 month (~0.08 yr).

Unfortunately, the assumptions underlying Eq. 3 are not always valid. In large parts of the lake, small but significant ⁴He excesses were found (i.e. ⁴He concentrations above the atmospheric solubility equilibrium as calculated from Weiss 1971). These excesses tend to increase with depth. In contrast, within experimental error, neon concentrations are always at atmospheric equilibrium (Aeschbach-Hertig 1994). These findings indicate the presence of radiogenic helium produced by α emitters in the crust. Radiogenic helium has a low ³He : ⁴He ratio, \( R_{\text{rad}} \), typically between 0.01 and 0.1 \( R_{\text{a}} \) (Lupton 1983).

If any atmospheric helium anomaly is excluded, an assumption supported by the neon data, the different helium components can be split as follows:

\[ ^{3}\text{He}_{\text{tri}} = ^{4}\text{He}_{\text{m}} (R_{\text{m}} - R_{\text{rad}}) - ^{4}\text{He}_{\text{eq}} (R_{\text{eq}} - R_{\text{rad}}) \]

(4)

where \(^{4}\text{He}_{\text{eq}}\) is the ⁴He concentration at solubility equilibrium. Though \( R_{\text{rad}} \), the ³He : ⁴He ratio of the injected radiogenic helium, is not precisely known, Eq. 4 can still be evaluated provided that \( R_{\text{rad}} \ll R_{\text{m}} \). Thus, whenever significant ⁴He excesses were present, Eq. 4 with \( R_{\text{rad}} = (5 \pm 5) \times 10^{-8} \) was used to calculate \(^{3}\text{He}_{\text{eq}}\). A disadvantage of Eq. 4 is that the error of \(^{3}\text{He}_{\text{eq}}\) (and hence of the water age) becomes larger than for Eq. 3 due to the influence from the error of \(^{4}\text{He}_{\text{m}}\) and the uncertainty of \(^{4}\text{He}_{\text{eq}}\), which is 0.5% (Weiss 1971).

Results

Here we discuss the main features of the distributions of density and ³H-³He water age in the lake to get a general understanding of the most important factors governing density-driven exchange. In the next section, simple mathematical tools are used to look at these processes in a more quantitative manner.
Fig. 2. Temporal evolution of water density $\rho$ along the longitudinal section shown in Fig. 1B. Values given in g m$^{-3}$, as $(\rho - 10^6 \text{ g m}^{-3})$. Vertical lines indicate the position of CTD profiles. A. 13 November 1990—predominantly horizontal isopycnals. B. 30 January 1991—almost vertical isopycnals above the sills. C. 17–18 April 1991—reduced horizontal gradients. D. 18 November 1991—horizontal isopycnals again.

**Density distribution**—To visualize horizontal density gradients between the basins of Lake Lucerne, we calculated isopycnals from CTD profiles and plotted them in the longitudinal section shown in Fig. 1B. A sequence of such graphs (Fig. 2) shows the development of the density distribution from November 1990 to November 1991, the period most intensively studied. Only isopycnals that refer to water temperatures of 6°C and less are shown. The large temporal and spatial density variations in the thermocline and epilimnion during summer are not relevant in this context.

In November 1990 (Fig. 2A), a distinct vertical stratification of the hypolimnion was present throughout the lake (no data from Alpnachersee). Horizontal density gradients were mostly small above the sills as well as within the individual basins below the sills. However, there were clear density differences between the deep water bodies that are separated by the sills. As expected from external forcing, Urnersee is weakly stratified and has the least dense deep water.

In January 1991, only 2 months later, the situation had changed completely (Fig. 2B). Alpnachersee was well mixed and had by far the highest density in the whole system, due to its low temperature (~3.7°C) and high salinity ($\kappa_{50} \approx 320 \mu$S cm$^{-1}$). Urnersee was rather homogeneous as well, but had a smaller density due to its high temperature (~5.6°C) and low salinity ($\kappa_{50} \approx 190 \mu$S cm$^{-1}$). Strong horizontal density gradients had built up between these two extremes, especially above the sills. The deep waters of Vitznauernensee and Gersauensee were still stratified and practically unaffected by the winter mixing.

In April 1991 (Fig. 2C), a new thermal stratification had developed near the surface. Horizontal gradients had
Density currents reach deepest in March and April, when stratification is weak. The potential of these currents to reach the very bottom of the basin is larger in Unersee than in Gersauersee. During summer, the depth differences of corresponding isopycnals in adjacent basins are reduced to ~30 m, but horizontal density gradients never disappear completely.

$^3$H-$^3$He water age distribution—A sequence of three longitudinal sections of $^3$H-$^3$He water ages spanning the period from November 1990 to November 1991 is shown in Fig. 4. Note that the spatial sampling density and the precision of individual data points are much smaller for the water age than for the temperature and electric conductivity used to draw Fig. 2. To indicate the reliability of the age structure shown in Fig. 4, we used dots to mark the sites where samples were taken. The 1σ uncertainty of an individual data point usually exceeds 0.1 yr but clearly remains below the 0.2-yr interval of the isolines shown in the graphs.

The restrictions imposed by the accuracy of the data become apparent if one attempts to use tritium as an independent tracer. In fact, the observed spatial variations are often of similar size as the experimental error (~0.8–1 TU). In November 1990, the tritium concentrations in the deep water of Gersauersee were still clearly greater than in the upper layers and in the other basins (~36 TU compared to 30 TU). Two years later, the tritium distribution was almost completely homogeneous at values of 27–28 TU. Only the rapidly flushed Alpnachersee and the surface waters of the major basins in summer showed distinctly lower tritium concentrations.
Although the rather homogeneous tritium distribution deprives us of an independent tracer, it allows us to at least interpret the water age as the weighted mean of the age of the mixing water bodies—an impossibility if water masses with very different tritium contents are mixed (Jenkins and Clarke 1976). For constant tritium concentration, water age is directly related to the concentration of tritiogenic 3He (Eq. 1 or 2). Thus, Fig. 4 can also be interpreted as a map of the 3He concentration in the lake, but the water age gives a more direct meaning of the distributions.

In November 1990 (Fig. 4A), the vertical stratification of the water age was clearly visible. The ages in the deepest part of Obermatt Basin (max, 2.7 yr) and Gersau Basin (max, 3.8 yr) indicate that the deep layers of these basins were not completely renewed during the preceding spring mixing period. In contrast, the age distribution in the hypolimnion of Urnersee was rather uniform. The deepest sample seems to indicate even a slight inversion (i.e., younger water lying below the older). The large wind-induced mixing in spring may explain the homogeneous age profile but not its large value. However, the sloping of the isolines from Gersau to Urnersee suggests that intrusion of relatively old water from intermediate depths in Gersau Basin could be responsible for both the great age and the inverse stratification of water in the deepest part of Urnersee.

Figure 4B combines data from samples taken in March 1991 in Alpnachersee and Big Cross Funnel and from samples taken a month later in the rest of the lake. This represents the most comprehensive 3H-3He data set we obtained. Alpnachersee was completely mixed and very young. There was an age inversion at the bottom of Big Cross Funnel (Sta. VI1 and VI5) that is substantiated by several samples (average ages for 50-m depth intervals are given in Table 2). Figure 4B clearly confirms the conclusion drawn from the density data (i.e., that water from Alpnachersee had been flowing into the basin along the bottom). Note that the age inversion had vanished in April when station VI5 was sampled again.

In Obermatt Basin, there was a remarkable homogenization and rejuvenation during winter 1990–1991, indicating strong vertical mixing. Rejuvenation was less effective in Gersau Basin, but the sloping isolines show that the deep water had not yet come to a rest in April. A comparison with the density distribution shown in Fig. 2C suggests that the horizontal age gradients in Gersau Basin were caused by a plunging flow of younger water from Obermatt Basin. The existence of a similar flow of older water from Gersau Basin into Urnersee is evidenced by the age distribution in the hypolimnion of the latter. Yet, in spite of the input of older water, the mean water age dropped by 0.4 yr in the deep hypolimnion of Urnersee after November 1990. This drop and the fairly homo-
Table 2. Mean water age in the boxes used for modeling water exchange.

<table>
<thead>
<tr>
<th>Box*</th>
<th>Vol. (10^6 m^3)</th>
<th>13 Nov 90</th>
<th>11 Mar 91</th>
<th>17-18 Apr 91</th>
<th>17-18 Apr 91†</th>
<th>18-20 Nov 91</th>
<th>23-24 Mar 92</th>
<th>21 Jul 92</th>
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<tr>
<td>AL</td>
<td>104</td>
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<td>0.96±0.07</td>
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</tbody>
</table>

*50-m-deep boxes (see Fig. 1B and text for definition) and the total of each basin are listed.
†Volume-weighted average calculated from the interpolated profile taken at the central station of each basin (boldface in Fig. 1B), except for second April 1991 column (see next footnote).
‡Calculated from profiles taken at the accessory stations GE1 and UR1 in Gersau Basin and Urnersee. For further calculations basin-wide averages were obtained by weighting the main stations (GE2 and UR2) 3 times higher than the accessory stations.

A distinct age stratification had developed in Alpnachsee. In Vitznauersee, the differences between Big Cross Funnel and Obermatt Basin had disappeared. The age at the bottom of Gersauersee did not increase after April and remained clearly below the values of the previous year, which could be explained as follows. In April 1991, water with an age of up to 1.4 yr flowed from Gersauersee into Urnersee across the sill, where it plunged to the bottom and increased the water age (Fig. 4B). When vertical mixing had stopped, the water age in the hypolimnion increased by roughly 1 month per month. At some time in summer, water from Gersauersee began to have a rejuvenating effect on Urnersee; however when this happened, the water no longer intruded at the bottom but at ~120-m depth (see Fig. 2D), where it produced the observed minimum.

Current measurements—In spring 1991, two acoustic current meters were moored on top of the sill between Vitznauersee and Gersauersee in order to directly demonstrate the existence of density-driven currents. Although the complex bottom topography at the sill put some constraints on the general validity of the data collected at only one location, interesting order-of-magnitude estimates could be obtained and checked with respect to their plausibility.

The upper current meter (depth, 30 m) registered only weak currents of a few centimeters per second, preferentially toward NW. Because of the E-W orientation of the sill, the N-S component of the velocity is relevant to net transport across the sill. Averaged over the whole recording period (12 April–26 May 1991), the N-S component was 0.18 cm s⁻¹ to the north (i.e. from Gersauersee into Vitznauersee). This number can be used to calculate a rough estimate for the net flow across the sill by multiplying it with the total cross-sectional area above the sill (~50,000 m²) to yield 90 m³ s⁻¹. The close agreement with the value calculated from the water balance of Gersauersee (88 m³ s⁻¹, Table 1) must be fortuitous, because the spatial variation of the velocity across the cross-sect-
tion as well as the absolute calibration of the current meter are unknown. Still, the measured current velocity seems to be of the right order of magnitude.

Of greater interest are the data recorded by the instrument at 44-m depth, roughly 1 m above bottom. Figure 5 shows a section of 16 d (14–29 April) of the N-S velocity component and of the simultaneously recorded water temperature. Although the NW current from Obermatt into Gersau Basin are coupled with low temperatures. The wind rose gives the frequency distribution of current directions during the entire observation period of 45 d.

Fig. 5. Time series of water temperature and N-S component of current velocity recorded close to Sta. VI4 (i.e. on top of the sill between Obermatt and Gersau Basins, see Fig. 1). The acoustic current meter was moored at 44-m depth, ~1 m above bottom. Strong southward currents from Obermatt into Gersau Basin are coupled with low temperatures. The wind rose gives the frequency distribution of current directions during the entire observation period of 45 d.

Discussion

A simple model for hydraulically controlled flow—The dynamics of the current velocity measured above the sill (Fig. 5) shows that probably influenced by seiche motion—the density flow is not continuous. In order to estimate the temporal mean of the exchange flow over such a sill, van Senden et al. (1990) used the two-layer model of Farmer and Armi (1986). Given two homogeneous layers of water with different densities, this model calculates the flow in each layer by assuming that at steady state the situation is controlled by a specific kind of criticality. The flow is called critical if the following condition holds:

$$F_1^2 + F_2^2 = 1,$$

with the internal Froude numbers

$$F_i^2 = \frac{Q_i^2}{g'h_iA_i^2}.$$

$$Q_i$$ denotes the volume flux, $$h_i$$ the thickness, and $$A_i$$ the cross-sectional area of the upper ($$i = 1$$) and lower ($$i = 2$$) layer. $$g' = (\Delta \rho/\rho)g$$ is the reduced gravity for the density difference $$\Delta \rho$$ between the layers, and $$g$$ is the gravitational constant. For a pure exchange flow, we can set $$Q_1 = -Q_2$$ and use the fact that in our case the upper layer is much larger than the lower (i.e. $$h_1A_1^2 \gg h_2A_2^2$$). Then Eq. 5 can be reduced to $$F_2^2 = 1.$$ Hence, the flux is controlled by the lower layer only and obeys the equation

$$Q_2^2 = g'h_2A_2^2.$$  

Equation 6 is equivalent to $$n_2 = (g'h_2)^{1/3} \left(\nu_2\text{ is the current velocity in the bottom layer}\right)$$, which is the speed of a shallow internal wave under the influence of reduced gravity $$g'.$$ For the sill between Treib Basin and Urnersee, van Senden et al. (1990) assumed $$h_2 = 10$$ m, $$A_2 = 3,000$$ m$^2$, and $$\Delta \rho/\rho = 5 \times 10^{-6}$$ and obtained a volume flux of 66 m$^3$s$^{-1}$ from Eq. 6, about half the value of 120 m$^3$s$^{-1}$ given by Wüst et al. (1988). Based on the current profiles mentioned above, we use $$h_2 = 5$$ m and $$A_2 = 2,000$$ m$^2$ for the sill between Vitznauerssee and Gersauerssee. With the typical value $$(\Delta \rho/\rho) = 10 \times 10^{-6}$$ (see Fig. 2C), we get a back flux of 44 m$^3$s$^{-1}$ in the bottom layer, in accordance with the value estimated from the current measurements. In conclusion, the model Eq. 6 is capable of reproducing the right order of magnitude for the mean flow across the sill. However, one should not forget that due to seiching in the basins on both sides of the sill, the real flow is time-variable and frequently changes its direction.

Calculation of exchange rates from age evolution in the individual basins—In this section, water age data are used...
to quantify deep water renewal by a simple inversion method. The accuracy of these calculations is limited by the temporal and spatial resolution of the data as well as by the analytical error. Hence, a model with a rather coarse resolution is applied. The lake is divided into well-mixed boxes, 50 m thick, and with horizontal size determined by the topography of the lake (see Fig. 1B). The boxes are named by the two-letter abbreviation for the basin plus a letter to indicate the depth of the layer: S (surface) for 0–50 m, I (intermediate) for 50–100 m, D (deep) for 100–150 m, and B (bottom) for the layer below 150 m. The volume-weighted average water ages of these boxes are listed in Table 2 and shown in Fig. 6.

For an isolated box, the water age \( \tau \) changes according to \( \frac{d\tau}{dt} = 1 \) (“closed system” arrows in Fig. 6). Any deviation from this behavior is attributed to exchange of water with adjacent boxes. Because water ages are generally small (i.e. well below the half-life of tritium) and tritium concentrations are fairly constant, the linear approximation Eq. 2 can be combined with a linear mixing model (Jenkins and Clarke 1976). The age balance for a selected box \( X \) is given by

\[
\frac{\Delta \tau_X}{\Delta t} = \frac{V_{ex}}{V_X} \left( \frac{\tau_X}{\Delta t} - \tau_{rX} \right) + 1. \tag{7}
\]

\( V_X (m^3) \) is the volume of selected box \( X \), \( V_{ex} (m^3) \) the exchanged water volume, \( \tau_{rX}, \tau_X \) (yr) the mean age of inflowing water and box \( X \), \( \Delta t \) (yr) the time between two consecutive sampling dates, and \( \Delta \tau_X \) (yr) the change of age between sampling dates. In Eq. 7, the first term on the right-hand side expresses age changes due to mixing, whereas the second term is the “source” term of the water age. Evaluation for the relative water exchange in box \( X \), \( \eta_X \), yields

\[
\eta_X = \frac{V_{ex}}{V_X} = \frac{\Delta \tau_X - \Delta t}{\tau_{rX} - \tau_X}. \tag{8}
\]

Note that Eq. 8 is only valid if \( \Delta \tau_X/\tau_X \ll 1 \) (i.e. if the relative exchange is small). For the evaluation of Eq. 8, it is assumed that box \( X \) exchanges water with only one or two of its neighbors. In Table 3, two types of neighbors of the selected deep-water boxes \( X \) are chosen: boxes vertically above box \( X \) to simulate pure intrabasin vertical exchange, or boxes from adjacent basins to describe lateral density-driven flow. Note that, based on one tracer alone (water age), it is not possible to quantify the relative importance of both processes—vertical and lateral exchange. Hence, the numbers of Table 3 require additional information as provided, for instance, by anomalous spatial and temporal patterns observed in the age distribution in the different basins.

Alpnachersee closely follows the picture of a temperate, annually mixing lake (e.g. Torgersen et al. 1977). From March through November, its hypolimnion behaves as a closed system. During winter circulation (December–February) it nearly reaches atmospheric equilibrium. Although Alpnachersee significantly contributes to the water exchange in its neighbor basin (Vitznauersee), it is not in turn influenced by its neighbor.

The mean water ages in the layers of Vitznauersee were highest at the beginning of the observation period (Fig. 6A), indicating weaker mixing during the preceding year(s). The ages follow a pattern of significant reduction during winter and closed-system increase (1 month age increase per month) during summer. Therefore, the exchange rates derived from Eq. 8 for the deep waters in both Big Cross Funnel (CFD) and Obermatt Basin (OMD) are large in
winter and not significantly different from zero in summer (Table 3). This pattern is expected for purely vertical exchange.

However, the water ages in Big Cross Funnel are generally lower than in Obermatt Basin, especially in spring (Fig. 6A). The younger age could result from either stronger vertical mixing (CF is more wind exposed than OB) or the inflow of young water from Alpnachersee. Compelling evidence for the second possibility is provided by the inverse age stratification in March 1991 (Fig. 6A). The younger age could result from either strong vertical mixing (CF is more wind exposed than OB) or the inflow of young water from Alpnachersee. Compelling evidence for the second possibility is provided by the inverse age stratification in March 1991, when the CFD water is significantly older than the underlying CFD water. This age inversion is accompanied by conductivity signals similar to the one shown in Fig. 3B (Aeschbach-Hertig 1994). According to a simple mixing calculation, the CFD water age of 0.5 yr as observed in March 1991 can be interpreted as a mixture of 65% CFI water (age 0.07 yr) and 35% water of zero age from Alpnachersee. Yet, conductivity data allow for only 6% water from Alpnachersee in the CFD box. This seeming contradiction might be resolved by assuming that surface water from the Big Cross Funnel is entrained into the AL outflow. An entrainment factor of 6 (i.e. a 6-fold increase of the AL volume by entrainment) would significantly lower the conductivity of the overflowing water but only slightly affect its age.

Hence the outflow from Alpnachersee of ~10 m³ s⁻¹ seems to generate a total flow of 60 m³ s⁻¹, which would be able to flush the small CFD volume within 6 d. It appears that during winter and spring, both vertical exchange and the density current from Alpnachersee strongly affect the CFD water. The competition between the two processes is illustrated by the sudden disappearance of the age inversion between March and April 1991, just after the supply of young and dense water from Alpnachersee had ceased.

As in Vitznauersee, the time series of water age in Gersauerssee and Treib Basin below 50 m (Fig. 6B) begin with the highest measured values in November 1990 followed by a distinct rejuvenation during winter 1990–1991. During both investigated winters, Gersauerssee remained stratified with respect to both age and density (Fig. 2). In fact, van Senden et al. (1990) never observed complete mixing (defined as the state when all vertical gradients have disappeared) in Gersauerssee in the years from 1965 to 1974. Yet, these findings do not rule out intrabasin vertical exchange as a major cause of the renewal of the deep water in winter. Rejuvenation of deep water without vertical homogenization has been observed even in lakes with simple one-basin topography (e.g. Imboden et al. 1983).

A clear indication of lateral exchange between Vitznauersee and Gersauerssee is provided by the large horizontal gradients between stations GE1 and GE2 in April 1991 (Fig. 4B). By interpreting the water at GE1 as a mixture of water from GE2 and the combined OMS+OMI volume and by assuming that station GE1 is representative for 25% of the GE volume (as done for the calculations leading to Table 3 and Fig. 6), we find that a total volume of at least 100 × 10⁶ m³ from Obermatt Basin must have flown into Gersauerssee in order to produce the observed horizontal gradients.

Table 3 yields an upper limit for the magnitude of the density-driven current: if lateral exchange from Vitznauersee was the only process of deep-water formation in GED+GEB, the exchange flows would be (240 ± 40) × 10⁶ m³ month⁻¹ in winter 1991 and

<table>
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<th>Selected box X*</th>
<th>Connected box†</th>
<th>Winter 91</th>
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<th>Winter 92</th>
<th>Summer 92</th>
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<td>5.8±1.9</td>
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<td>0.3±3.9</td>
<td>47±100</td>
<td>-3.1±5.4$</td>
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</table>

*The selected box X for which the exchange rates are calculated according to Eq. 8. Box X can be a combination of two of the basic boxes shown in Fig. 1B.
†The box (or combination of two boxes) which exchanges water with box X. Two extreme scenarios are chosen: purely vertical exchange (upper line for each X) and purely lateral exchange (lower line).
§Exchange rate negative because Δτ/Δt > 1.
$Not enough data to calculate exchange rate.
¶Exchange rate negative because AT/Δt > 1.
According to the CTD data, density-driven water from Vitznauersee combined with an export of older water to Urnersee. The water renewal must result primarily from the import of young water from Vitznauersee and the export of older water to Urnersee. Provided that during summer periods the flow from the OMS+OMI volume was the only significant process to renew the water in Gersauersee below 100 m (GED+GEB), the flow during the summer must have been $100 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ in 1991 and $80 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ in 1992. According to the CTD data, density-driven water from Vitznauersee could only penetrate into the layers below 100 m of Gersauersee until June. Hence, the real monthly flow in spring must have been larger.

As in Gersau Basin, the renewal of deep water in Treib Basin is not stopped during summer, indicating lateral exchange. The exchange rates calculated for this process suggest rapid flushing of the Treib Basin. The corresponding volume flux can easily be supplied by the density current from Gersauersee into Urnersee of $260 \pm 40 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ in winter 1992. These values are larger than the ones derived from current measurements and the hydraulic model ($100 \times 10^6 \text{ m}^3 \text{ month}^{-1}$), even though they are averages over the whole winter, including times of weak density gradients. Although the exact split between vertical mixing and lateral exchange cannot be determined, it seems likely that both processes play an important role in the deep-water renewal of Gersauersee during winter.

In summer, water age in the deep layers of Gersauersee remained rather constant (Fig. 6B), which results in quite large (vertical or lateral) exchange rates (Table 3). As concluded from the development of a distinct thermocline early in spring, intrabasin vertical mixing cannot explain this observation. The water renewal must result primarily from the import of young water from Vitznauersee combined with an export of older water to Urnersee. Provided that during summer periods the flow from the OMS+OMI volume was the only significant process to renew the water in Gersauersee below 100 m (GED+GEB), the flow during the summer must have been $100 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ in 1991 and $80 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ in 1992. According to the CTD data, density-driven water from Vitznauersee could only penetrate into the layers below 100 m of Gersauersee until June. Hence, the real monthly flow in spring must have been larger.

As in Gersau Basin, the renewal of deep water in Treib Basin is not stopped during summer, indicating lateral exchange. The exchange rates calculated for this process suggest rapid flushing of the Treib Basin. The corresponding volume flux can easily be supplied by the density current from Gersauersee into Urnersee of $300 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ (Wüest et al. 1988).

At first sight, the temporal changes of water age in the deep water of Urnersee (Fig. 6C) and the corresponding vertical exchange rates (Table 3) look as expected for a lake that mixes annually: strong rejuvenation in winter followed by a closed-system age increase in summer. However, a closer look reveals structures that cannot be explained by internal vertical mixing alone. There are indications for occasional age inversions (i.e., for situations in which older water overlies younger).

The water age profiles measured in November 1990 at position UR2 showed a maximum between 115 and 182 m (Fig. 4A). It may be more than a coincidence that the age in the URD box was practically identical with the age measured in TRI and TRD (see Table 2 and Fig. 6C). From the vertical density distribution, we can see that water from Treib Basin plunged into the URD volume between July and November. Hence, a plausible explanation for the age inversion is that roughly the whole volume of URD ($750 \times 10^6 \text{ m}^3$) had been replaced during the preceding 5 months (i.e., that a flux of $150 \times 10^6 \text{ m}^3 \text{ month}^{-1}$ was flowing from Gersauersee through Treib Basin into the deep water of Urnersee).

In November 1991, a local minimum (another age inversion) was observed in the URD box. Again, this can be explained by the influence of water from Treib Basin. By interpreting the URD water as a mixture of equal water volumes from Urnersee (URI) and Treib Basin (TRI+TRD), we can calculate an average flow of $(90 \pm 50) \times 10^6 \text{ m}^3 \text{ month}^{-1}$ for the period from July to November 1991. This is about a third of the corresponding flow estimated by Wüest et al. (1988) for May–June 1986. As shown by these investigators, a consequence of the plunging flow from Gersauersee into Urnersee is an upwelling in the latter basin. This upwelling perfectly explains the rather rapid aging in URI observed in summer 1991 (Fig. 6C).

Calculations of the lateral exchange rates by Eq. 8 are inconclusive for the Treib Basin–Urnersee system (Table 3) because the average ages of the involved boxes are very similar. As in the case of the Gersau Basin–Treib Basin system, this similarity suggests a strong coupling between the respective boxes.

During the 7 months (0.59 yr) between 18 April and 18 November 1991, the volume-weighted mean water age below 50 m increased by $55 \pm 0.07$ yr in Vitznauersee $(CF+OM), 0.09 \pm 0.07$ yr in Gersauersee $(GE+TR), 0.70 \pm 0.09$ yr in Urnersee, and $0.40 \pm 0.05$ yr in the whole lake (see Table 2). From these figures, we conclude that the hypolimnion of Vitznauersee behaves almost like a closed system; that Gersauersee exports its old water to Urnersee, thus keeping the age of the former nearly constant and causing an excessive age increase in the latter; and that the hypolimnion of the lake as a whole is not completely closed during summer (the observed age change represents only 67% of the real time). Because of its vertical density structure and wind exposure, Urnersee has the largest intrabasin exchange with surface water—in spite of its excessive age increase during the summer.

**Helium flux and oxygen utilization**—The lateral flow of water between the basins of the lake affects the spatial distribution of all dissolved species. From an ecological point of view, transport and depletion of dissolved oxygen is of great interest, whereas geochemists might be interested in the flux of helium from the ground. Because the involved species—helium and dissolved oxygen—both equilibrate at the water surface, water age is an ideal tracer to study processes, such as in situ consumption, that affect their distribution. Yet, an absolute linear correlation between water age (which is really excess $^3$He, if tritium is constant), excess $^4$He, and oxygen could only evolve, provided that two conditions are fulfilled: for all components, the in situ production-consumption per unit volume and time is constant throughout the lake, and the air-water exchange velocity at the lake surface is identical for all components (though it may vary with time and area).

Both conditions are not strictly valid. Whatever model is adopted, air-water exchange is faster for the light helium than for the heavier molecular oxygen (e.g., Ledwell 1984). Furthermore, since the concentration of tritium is fairly constant, $^3$He has a homogeneous volume source. In contrast, helium from the interior of the earth is released at the bottom of the lake (areal source). Thus, even if the flux per unit area were constant, the source of $^4$He per unit volume would depend on the basin-specific volume per area ratios (i.e., the mean depths of the basin).
Finally, oxygen is consumed both in the open water column (volume sink) and at the sediment surface (areal sink) (e.g. Livingstone and Imboden 1996).

Nonetheless, linear correlations of water age with $^4$He excess and oxygen deficit, respectively, yield valuable information on the mean helium flux from the crust as well as on the average oxygen consumption in the water column, although there is considerable residual variation (Fig. 7). The slope of the regression lines gives the consumption-production rate per volume. If multiplied with the basin mean depth, the slopes yield these rates on a per area basis (Table 4). Note that a similar correlation with water exchange time (the inverse of the exchange rates listed in Table 3) instead of water age would not be meaningful because the inflowing water may already have a certain age as well as an oxygen deficit or helium excess, especially if it originates from another deep-water box.

The area-specific helium fluxes obtained for Alpnachersee, Vitznauersee, and Gersauersee range between 1.1 and $2.2 \times 10^{10}$ atoms m$^{-2}$ s$^{-1}$ (Table 4). These values are comparable with literature values for the flux of helium from average continental crust ($\sim 3 \times 10^{10}$ atoms m$^{-2}$ s$^{-1}$) as calculated based on the assumption that this flux is in equilibrium with the total crustal radiogenic helium production (O'Nions and Oxburgh 1983; Torgersen and Clarke 1985). Most experimental values of continental helium fluxes are determined from helium accumulation rates in lakes or groundwater and are typically in the order of $10^{10}$ atoms m$^{-2}$ s$^{-1}$ (e.g. O'Nions and Oxburgh 1988; Stute et al. 1992; Marty et al. 1993). Hence, helium fluxes in the basins of Lake Lucerne are in accordance with the hypothesis of steady-state degassing of radiogenic helium from the crust.

An additional helium source seems to be present in Urnersee. The flux calculated from the $^4$He: age correlation is $(14 \pm 5) \times 10^{10}$ atoms m$^{-2}$ s$^{-1}$. Taking into account that the flow from Gersauersee adds water with a lower $^4$He: age ratio to Urnersee, the $^4$He: age production ratio in Urnersee alone must be even larger. Different mixing ratios between water from Gersauersee and Urnersee cause the large scatter of the $^4$He: age data points measured in Urnersee (Fig. 7A). Because the density current from Gersauersee mainly affects the lower layers of Urnersee, larger $^4$He: age ratios are expected for the upper hypolimnion. In fact, the largest $^4$He: age ratios are observed above 100 m. The corresponding regression line of the data from above 100 m yields a helium flux of $20 \times 10^{10}$ atoms m$^{-2}$ s$^{-1}$.

As suggested by Mamyrin and Tolstikhin (1984) in their comment on the data of Torgersen and Clarke (1978) from Tegagu Lake (Canada), high helium fluxes in lakes might be related to input of helium-rich groundwater rather than to unusually high uranium concentrations. According to the hydrogeological situation, such groundwater input into Urnersee seems plausible (Schindler pers. comm.). However, there is no further evidence for subaquatic springs in the lake, and hence the question of the origin of the large helium flux into Urnersee remains open.

Oxygen deficit, $\Delta O_2$ (i.e. the difference between atmospheric saturation at the measured water temperature), and the measured oxygen concentration, is plotted against water age in Fig. 7B. In Table 4, two extreme scenarios of oxygen depletion are considered, according
to which oxygen is only depleted either in the water column (depletion rate per unit volume) or at the sediment surface (depletion rate per unit area). In reality, both processes must occur simultaneously, but their relative weight cannot be determined with these data.

Mean volumetric oxygen depletion rates are close to 2 g m\(^{-3}\) yr\(^{-1}\) for the deep basins of Gersauersee and Urnersee. These values compare well with the middepth depletion rates determined by van Senden et al. (1990) from a 10-yr data record (1965–1974). The depletion rates for individual samples, calculated as the ratio of oxygen deficit and age, confirm the vertical structure of the depletion rate observed by van Senden et al., although the maxima in the metalimnion and near the bottom are less pronounced (Aeschbach-Hertig 1994).

Greater volumetric oxygen depletion rates are found in Vitznauernsee (2.9 g m\(^{-3}\) yr\(^{-1}\)) and especially in Alpnachersee (10 g m\(^{-3}\) yr\(^{-1}\)). However, if the oxygen consumption is related to the basin surfaces, all parts of the lake have roughly the same depletion rate per unit area, ~250 g m\(^{-2}\) yr\(^{-1}\) (last column of Table 4). The differences in the volumetric depletion rates seem to be closely related to the morphometry of the basins.

Conclusions

A detailed study of the spatial distribution of water temperature and salinity in Lake Lucerne shows that lakes with complex topography may develop horizontal density gradients that last for several months and may cause a rather complex pattern of interbasin exchange of water. In the case of Lake Lucerne, the density and pressure gradients have their origin in the geology of the drainage area of the lake. Because water temperatures in deep temperate lakes are mostly around 4°C (except for the upper 20–30 m), the thermal expansion of water is less relevant for the establishment of density gradients than is the spatial variation of the chemical composition of the water as produced by the tributaries originating from different geological environments. Geology, aided by the different wind forcing, is the main stimulus that produces the unique deep-water circulation of the lake. Other lakes of similar complexity still await discovery.

The existence of density-driven exchange between the basins of the lake is clearly demonstrated by the spatial and temporal evolution of the \(^{3}\)H-\(^{3}\)He water age. CTD measurements, especially the spatial structure of electric conductivity and water density, reveal the driving forces that cause the particular water age structure. Some direct measurements of currents confirm the presence of density driven flow. Quantification of the involved volume fluxes was attempted by using a simple model of density-driven flow over a sill, by the current velocity data, and by the \(^{3}\)H-\(^{3}\)He ages. In some basins it is possible to separate the respective contributions from vertical mixing and horizontal density currents to the local deep water renewal.

Horizontal gradients of water density are mainly produced in winter and largely disappear in summer, when thermal stratification shields off the deep layers from external influences. During winter, density-driven currents transport water from Alpnachersee into Big Cross Funnel, from Obermatt Basin into Gersau and Treib Basin and further into Urnersee. In most parts of the lake, this flow is directed against the main drainage direction of the lake and its tributaries.

In winter, when Alpnachersee is completely mixed vertically, its outflow of \(\sim 25 \times 10^{6} \text{ m}^{3} \text{ month}^{-1}\) by entrainment generates a plunging flow of \(\sim 150 \times 10^{6} \text{ m}^{3} \text{ month}^{-1}\), which flushes the volume in Big Cross Funnel below 100 m in a few days. The intensity of deep water renewal in Obermatt Basin by vertical mixing varies from year to year. In winter 1990–1991, when vertical exchange across the 100-m depth contour was exceptionally strong, a volume of \(\sim 1,000 \times 10^{6} \text{ m}^{3}\) was exchanged, more than twice the corresponding deep-water volume. In Gersau Basin a density-driven flow of the order of \(100 \times 10^{6} \text{ m}^{3} \text{ month}^{-1}\) replaces a significant part of the deep water below 100-m depth in spring. Yet, intrabasin vertical mixing also seems to be a major cause of the deep-water renewal of \(\sim 80\%\) during the cold season. For the deep water of the small Treib Basin the density-driven flow from Gersau Basin is important throughout the year. The size of the flow into Urnersee in spring was estimated by Wüest et al. (1988) as \(300 \times 10^{6} \text{ m}^{3} \text{ month}^{-1}\). Our investigation shows the existence of a reduced flow (\(\sim 100 \times 10^{6} \text{ m}^{3} \text{ month}^{-1}\)) during summer which, however, cannot penetrate into the deepest layer of Urnersee. Even though in Urnersee deep-water renewal by density-driven flow amounts to 25% per month, vertical mixing in spring is the dominant process that causes a water exchange of 2–3 times the volume below 100 m.

The flux of radiogenic helium into the lake of (1–2) \(\times 10^{10}\) atoms m\(^{-2}\) s\(^{-1}\) indicates dynamic equilibrium with the helium production in the underlying crust. However, for Urnersee the helium flux is larger by about one order of magnitude. Groundwater input may be responsible for this enhanced flux.

Mean oxygen depletion rates are in the order of 2 g m\(^{-3}\) yr\(^{-1}\) in the deep basins of Lake Lucerne and \(\sim 10\) g m\(^{-3}\) yr\(^{-1}\) in the shallow Alpnachersee. The difference may be due to the higher trophic state of Alpnachersee or simply to its smaller mean depth. Oxygen consumption related to the basin area is roughly equal in all basins, ranging from 220 to 290 g m\(^{-2}\) yr\(^{-1}\).

References


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