

Gas exchange with the atmosphere and internal mixing of Lake Constance (Obersee)

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Gasaustausch und innere Mischung umfassen verschiedene physikalische Prozesse, nämlich die Aufnahme und Abgabe von Gasen an der Seeoberfläche, die Gaserneuerung während der Vollzirkulation, die vertikale und horizontale turbulente Mischung und die Wassererneuerung in einem See. Diese Prozesse wurden durch Messung und Auswertung der Verteilungen der Isotope Tritium, Helium-3 und Radon-222 für den Bodensee untersucht.

Die Tritiumverteilung im See während der Jahre 1963 bis 1974 ergibt, daß jährlich etwa 15% des Tiefenwassers während der Vollzirkulation und 14% während der Sommerstagnation erneuert werden. Für den Gasaustausch mit der Atmosphäre während der Winterzirkulation 1976/77 wurden Evasionsraten für Helium-3 zwischen 2.2 und 3.9 m/d errechnet. Aus der Verteilung von Überschuß - Radon-222 unmittelbar über dem Boden des Sees ergaben sich vertikale Mischungskoeffizienten für diese Schicht zwischen 0.1 und 0.3 cm²/s. Das Projekt wird fortgeführt mit dem Ziel, die genannten Prozesse zu quantifizieren. Dies ist nicht nur ein Beitrag zum Verständnis der Dynamik des Sees, sondern die Ergebnisse lassen sich darüber hinaus auch anwenden, um quantitative Aussagen über die Umsätze biologisch aktiver Substanzen wie CO₂, O₂, Phosphat etc. zu erhalten und versprechen damit ein besseres Verständnis der biologischen und chemischen Vorgänge in einem See.

I. The deep water turnover of Lake Constance - a tritium study

Tritium, a heavy isotope of hydrogen, is present in nature as a radioactive tagged water molecule: HTO. It has been added to terrestrial waters since 1952 mostly by atmospheric nuclear weapon testing; the background to this "bomb" tritium from "natural" tritium (~5TU) is negligibly small (ROETHER 1967, WEISS 1972). Fig. 1 presents the history of rain tritium concentrations in the Lake Constance area (ROETHER 1970) between 1952 and 1976, showing atmospheric tritium pulses in 1954, 1958/59 and, predominantly,

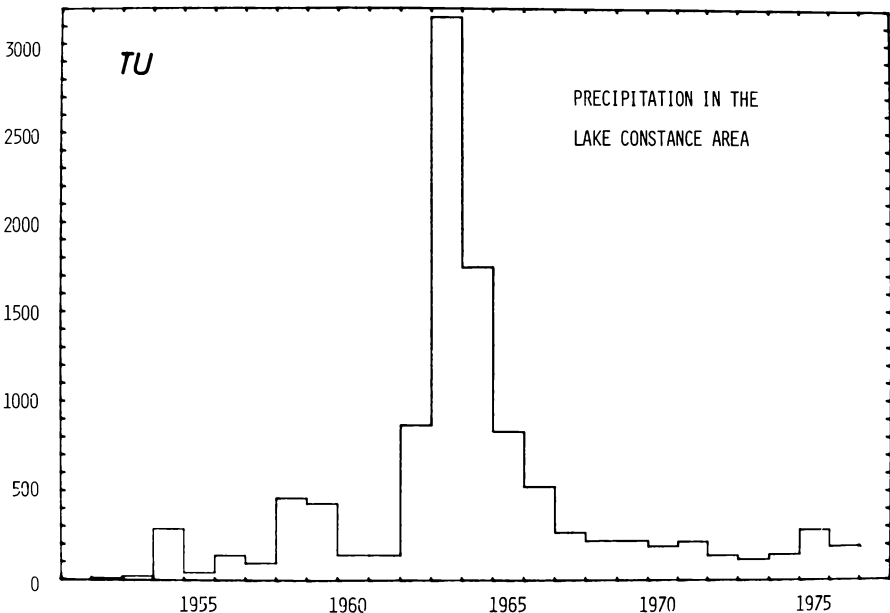


fig. 1: Yearly means of the average precipitation tritium concentrations in the Lake Constance area.

Concentrations are given in TU: $1 \text{ TU} = \frac{[T]}{[H]} = 10^{-18}$ or 3.2 pico Curie/l water. The averages were interpolated from recordings of several tritium stations in Central Europe by a procedure described by ROETHER (1970).

in 1963. After the test moratorium in 1963, the atmospheric tritium concentrations decreased exponentially between 1963 and 1968, and were nearly constant since then. Owing to the influence of tritium releases from nuclear industry installations, we observe a small peak in 1975 (WEISS et al. unpubl.). From the atmosphere, tritium has been incorporated into Lake Constance by rainout and vapour exchange over the lake surface (WEISS et al. unpubl., IMBODEN et al. 1977) and mostly by river inflow, about 70% of which is from the Alpenrhein (KIEFER 1968). It was the aim of this investigation to study the response of the lake to the known tritium supply, in order to extract quantitative information about the lake's water renewal.

Fig. 2 summarizes the experimental results. It is obvious from the 1963-66 data that most of the tritium, i.e., the newly added water, is supplied to near surface strata of the lake (LEHN 1978). In addition, the surface tritium concentrations nicely reflect the effect of the vertical stability of the lake: they are maximal during periods of high stability, i.e., little vertical mixing with deep water of low tritium concentrations and minimal during the overturn of the lake. The deep water tritium concentrations of the lake increased steadily between 1963 and 1966 thus reflecting the gradual renewal of this water mass. From 1967 onwards the lake can be assumed homogeneous vertically. Its average tritium concentration has decreased linearly since then, and reached concentrations of about 180 TU in 1976. The Alpenrhein, which provides most of tritium to the lake, acts as an effective source only during the years 1963-66 when its tritium concentrations were up to a factor of 2 higher than that of the lake surface, whereas after 1967 it rather dilutes the tritium concentrations.

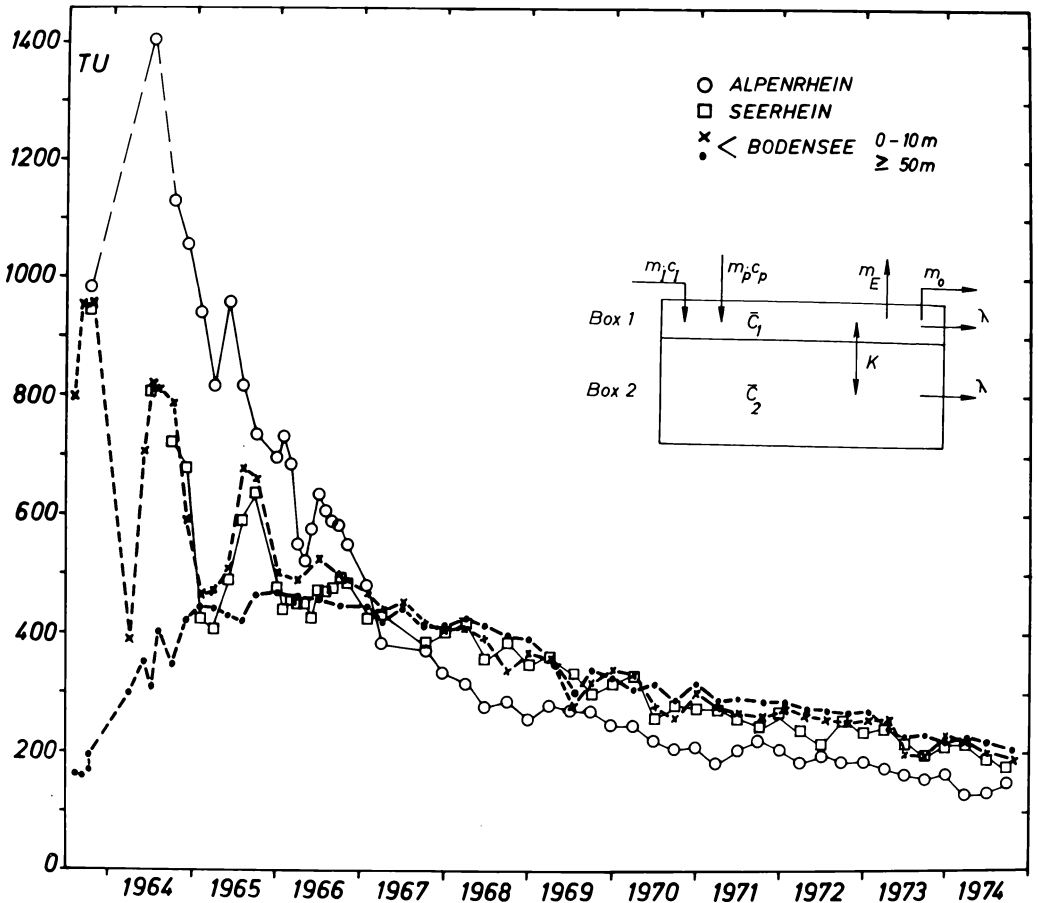


fig. 2: Experimental tritium concentrations for the Alpenrhein, the Seerhein and Lake Constance. The lake samples were taken in the center of the lake between the cities of Langenargen and Arbon. The lake data points are averages of 3 (0-10 m depth) and 4 measurements (\approx 50 m depth) resp. The insert shows a sketch of the two-box model used for the quantitative evaluation of the data.

The discharge of Lake Constance (Obersee) is by the Seerhein. Compared to the known vertical tritium distribution in the lake, the experimental tritium concentrations of the Seerhein indicate which strata of the lake contribute to the discharge. As is evident from fig. 2, most of the discharge comes from surface-near strata. During special weather conditions and weak vertical stability of the lake, however, strata from 50 m depth or more contribute to the discharge. Such events, observed early 1967 and 1966 (cf. fig. 2), are also reported by LEHN (1978).

From a quantitative interpretation of the data presented in fig. 2, the deep water turnover of the lake can be estimated. The estimate is based on a time dependent two box model, a sketch of which is shown in the insert of fig. 2. The model divides the lake vertically into two well mixed reservoirs. Tritium is added to the surface water box at a known annual rate by river inflow and rainout/vapour exchange, tritium loss is by evaporation, river outflow and radioactive decay. The renewal of the deep water box is by vertical mixing across the interface between the two boxes and by the overturn of the model lake at the end of each year. The renewal of the deep water during the overturn is given by the volume ratio g of the two boxes. From temperature and other observational data, g is chosen to be 0.15, which corresponds to a turnover time of 6.7 years. In addition to this channel, renewal of the deep water is by vertical mixing across the box interface. The mixing rate is characterized by a mixing coefficient K which is the only parameter of the model. Model calculations have been performed for various choices of K . A best fit of the experimental data was obtained for $K = 14\%$ per year or $1/K = 7.4$ years, which means that the apparent vertical mixing during the stagnation is almost as efficient for the renewal of the deep water of Lake Constance as the overturn of the lake. Certainly, the real mixing across the thermocline is much slower than mixing required by the model fit. In reality the additional mixing is due to the fact that after entering Lake Constance the Alpenrhein goes down to depths which correspond more or less to that of the thermocline in the open water and thus from time to time renews the deep water directly (cf. ELSTER a. EINSELE 1937, LEHN 1978).

It has often been proposed in the literature (McEWEN 1929, IMBODEN 1973, JASSBY a. POWELL 1975) to use the vertical temperature distribution in a lake for an evaluation of the apparent vertical mixing. The idea behind this "temperature or heat method" is that heat, like tritium, enters the lake at its surface and is then transported to greater depth by vertical mixing. For the purpose of this paper the geometry of the "tritium" model is used. The apparent vertical diffusivity between two observations can then be calculated from the average temperature gradient between the two boxes and the temperature gain of the deep water box. For the evaluation of the heat method, temperature profiles regularly available for a set position in the Obersee over a period of 14 years (1963-1977) were used. The processing of the data included the calculation of long term average box-temperatures twice a month. From the half-monthly averages the

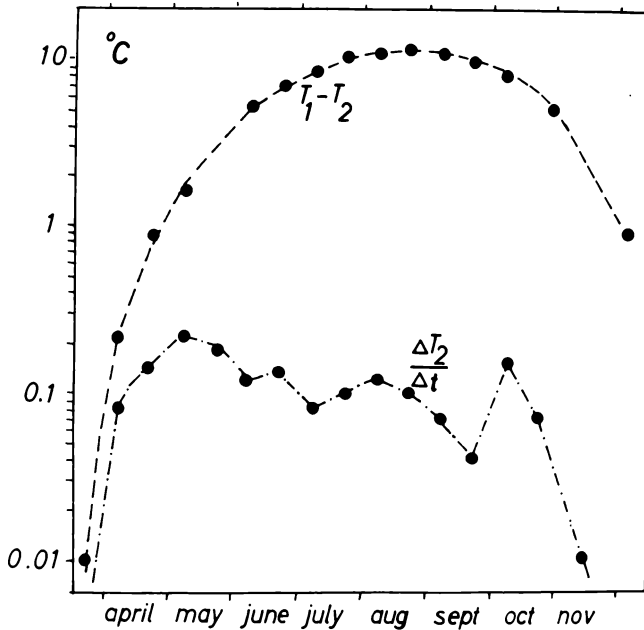


fig. 3: Long term average of the vertical temperature gradient in Lake Constance ($T_1 - T_2$) and average temperature gain of the deep water per fortnight $\frac{\Delta T_2}{\Delta t}$.

temperature gradients between the two boxes and the temperature gain of the deep water box per fortnight were calculated. The results are shown in fig. 3. Starting with a very weak vertical stability at the end of March ($\Delta T \approx 0.01^\circ\text{C}$) the vertical gradients increase rapidly during spring and early summer to reach values of about 10°C in summer. In fall the stability becomes weaker and a rapid drop of the vertical temperature gradients down to 1°C is observed in November. The average temperature gain of the water per fortnight is fairly small, i.e., 0.1°C , as compared to the precision of the temperature measurements and the lateral temperature inhomogeneities of the lake. This means that more and extremely precise temperature measurements are needed for the application of this method. One way to achieve this is to use long term averages, as we did, another more promising way would be to use a high precision temperature probe instead of reversing thermometers for the temperature registration, a method commonly used in oceanographic work. At the present time, the applicability of the temperature method seems to be limited by the data quality. This is illustrated by the fact that the method didn't work between December and March, the gradients being extremely small during that time. From the data presented in fig. 3, apparent vertical diffusivities were calculated. The values obtained are anticorrelated to the seasonal trend of the vertical stability of the lake with high values in spring and much lower and constant values during the summer. Compared to the results of the tritium method they are very similar: the difference between the yearly average of the vertical mixing coefficient as calculated from the temperature method and that obtained by the tritium method is about a factor of two only, most of this difference being certainly due to the uncertainties of the temperature method.

II. Tritium/helium-3 study

Helium-3 is a stable isotope of the noble gas helium. One of the sources for environmental helium-3 (JENKINS et al. 1972) is the decay of tritium; for Lake Constance with its high bomb tritium concentrations of about 180 TU (cf. above), tritium decay provides a strong source for helium-3 (so called "tritiogenic" helium-3). Combined tritium/helium-3 measurements, as recently introduced into limnological research by TORGERSON et al. (1977) give quantitative information about the processes of gas exchange, gas renewal during overturn, the rate of vertical mixing, and the water mass age.

Gas exchange

Gas exchange during the overturn of Lake Constance was studied during winter 1976/77. The basic idea is that large amounts of tritiogenic helium-3 are continuously produced by tritium decay in the water, so that an oversaturation of the lake water relates to its solubility equilibrium with the atmosphere results. The excess helium-3 is lost to the atmosphere by evasion. Use had been made of the fact that during summer stratification the loss of helium-3 to the atmosphere is primarily restricted to the epilimnion; due to highly reduced vertical exchange of water across the thermocline the loss of tritiogenic helium-3 from below the thermocline is small. As a result, large amounts of excess helium-3 are accumulated in the hypolimnion during the stratification of the lake. During the overturn of the lake this excess helium-3 mixes over the whole water column and is then available for evasion. Evaluation of the gas exchange rate from the experimental data is made by comparing the helium-3 content of the lake at two successive observations: The difference in the depth-integrated helium-3 content of the lake, corrected for tritium decay between the two observations is a direct measure of the gas exchange rate during the sampling interval. In the present study the intervals between individual samplings were roughly one month; according to the precision of the helium-3 measurement, however, intervals down to a few days show measurable variations already.

Fig. 4 shows the helium-3 results together with other relevant information. The first helium-3 profile was taken in November 1977 when the vertical stability of the lake was still high. Starting from a small helium-3 excess near the surface, the helium-3 concentrations increase rapidly with depth to a fairly constant value below 70 m. The time between the first and second profile was characterized by strong winds and low air temperatures (average wind speed at Friedrichshafen weather station (DEUTSCHER WETTERDIENST 1976/77): 3.5 m/sec), which considerably reduced the vertical stability of the lake. As a result of this, profile 2 shows that the loss of the excess helium-3 by mixing and evasion has already reached fairly large depths (cf. also oxygen profile). Below 100 m depth, however, the helium-3 concentrations are almost the same as observed in the first profile. This means that the water mass below 100 m was not very much affected yet by vertical mixing. This latter finding is of special importance for the interpretation of the oxygen data near the bottom.

Between the second and third profile the wind speed over the lake was much lower (average wind speed at Friedrichshafen weather station: 2.5 m/sec). Nevertheless, the vertical stability of the lake was now close to zero and helium-3 was lost almost down to the bottom.

For a quantitative interpretation of the data, gas exchange models are used (cf. MÜNNICH a. FLOTHMANN 1975, MÜNNICH et al. 1977, DEACON 1977). It can be shown that the evasion rate of helium-3 is characterized by an evasion velocity w by which helium is pushed out of the water, and by the difference between the helium-3 concentrations actually observed in the surface-water of the lake and the concentration corresponding to

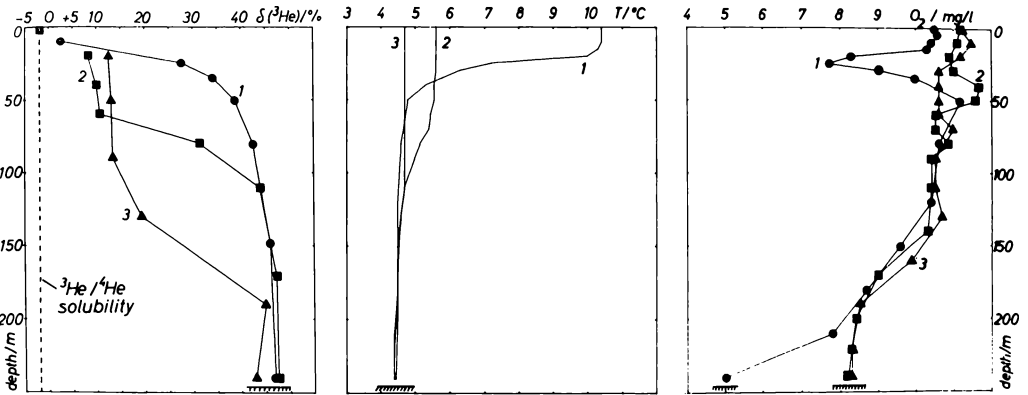


fig. 4: Temperature, oxygen, and helium-3 profiles taken in the center of Lake Constance (Obersee) between the cities of Immenstaad and Uttwil during the overturn of the lake in 1976/77.

(1 = 9. November 1976, 2 = 16. December 1976, 3 = 13. January 1977). The helium-3 concentrations are given in the δ -notation, i.e., as relative deviation of the helium-3/helium-4 ratio in the water from that of an air standard $\delta(^3\text{He}) = \left[\frac{(^3\text{He})/(^4\text{He})_{\text{water}}}{(^3\text{He})/(^4\text{He})_{\text{air}}} \right] \cdot 100$.

Dashed line gives the value of water in equilibrium with the atmosphere; small line with hatching in 250 m depth corresponds to bottom depth. Tritium/helium-3 ages can be calculated from the experimental helium-3 data on the basis of an average tritium concentration of the lake of 178.5 ± 1.3 TU and assuming ^4He to be in equilibrium with the atmosphere.

equilibrium with the atmosphere. It is one of the advantages of these models that, once the gas exchange rate is measured, i.e. w is known, the exchange rates for any other gas of interest for example CO_2 , O_2 ... can be calculated. From the experimental helium-3 data values of 3.9 m/d and 2.2 m/d were calculated for w for the intervals between the first and second resp. the second and third sampling. It is obvious from the wind data given above that wind speed/wind stress is an important factor controlling the gas exchange (cf. also MÜNNICH et al. 1977).

The results were used in order to understand the oxygen budget of the lake during that time: from the known evasion velocities for helium-3 the oxygen uptake rates of the lake were calculated (oxygen concentrations in the lake were below saturation). With the theoretical oxygen uptake rates the changes in the oxygen content of the lake, observed in fig. 4, could be explained.

Tritium/helium-3 ages

Another application of combined tritium/helium-3 measurements is to give an "age" τ of the water (cf. TORGERSON et al. 1977). This age is to be interpreted in the following way: as long as a tritium-containing parcel of water is near the surface and its helium-3 content is in equilibrium with the atmosphere, by definition its "age" is zero. As soon as the parcel becomes isolated from the atmosphere, excess helium-3 is being built up by tritium decay. The amount of excess helium-3 which will be found in the parcel after a certain time span τ is determined by the radioactive decay law. If the water parcel acts as a closed system τ corresponds to its "true" age, i.e., the time elapsed since the water has lost contact with the atmosphere. If, however, helium-3 is lost to some extent from the system (open system), an "apparent" age, i.e., a lower limit for τ can be calculated, which may be interpreted as the time of effective isolation of that water mass from the atmosphere.

In Lake Constance (cf. fig. 4) the observed tritium/helium-3 ages vary between a few months in shallow waters, and 15 months in the deep water. The tritium/helium-3 ages of the water masses in 25 m and at the bottom of the lake respectively (first profile, oxygen minima) will be discussed more specifically in the following. The oxygen minimum below the thermocline (25 m depth) is a well known limnological feature. It is due to biological activity in this region combined with the isolation of this water mass from the oxygen-rich water of the epilimnion. A tritium/helium-3 age of 8 months is cal-

culated for this water mass in November 1976. Fig. 5 shows the evolution of its oxygen concentration during the year 1976. It is seen that between January and March an oxygen deficit, remaining from the year before, is gradually being filled up by oxygen uptake from the atmosphere. Equilibrium with the atmosphere is observed in March, followed by an oversaturation up to 10% in May which is due to biological activity in the lake and a linear decrease of the oxygen concentrations from June onwards, to reach a minimum of 70% saturation early in November. The tritium/helium-3 age of 8 months of the water mass in November nicely agrees with the time elapsed since oxygen has been in equilibrium with the atmosphere (about March). In this case, thus, the tritium/helium-3 age gives the "true" age of the water mass. It is hoped that better knowledge of the date when the isolation from the atmosphere started will improve the oxygen budget of this layer.

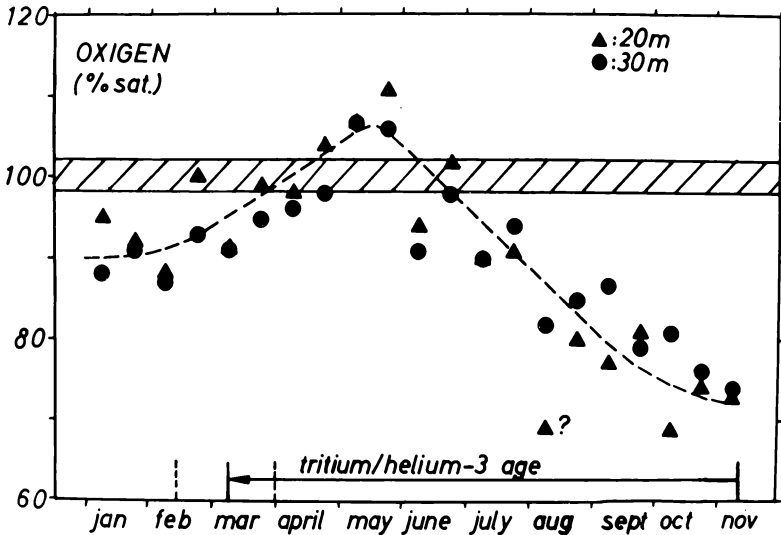


fig. 5: Oxygen concentrations in Lake Constance in 20 and 30 m depth resp. during 1976. Hatched area gives the uncertainty of the data points at saturation. Vertical lines give the time interval (1 sigma) during which the water mass lost contact with the atmosphere: tritium/helium-3 age.

The tritium/helium-3 age of the deep water as observed in November 1976 is about 14 months. Assuming the deep water to be a closed system would mean that the deep water had been in equilibrium with the atmosphere in September 1975 and had been isolated since then. This interpretation, of course, is in contradiction to the limnological knowledge about the overturn of the lake in 1975/76. Since, however, the tritium study supported the assumption that the deep water is a closed system we must conclude that only part of the deep water, which will furtheron be called "young" water, has been in equilibrium with the atmosphere during the overturn 1975/76, i.e., its tritium/helium-3 "clock" was set zero, whereas the remaining "old" water has not been in equilibrium with the atmosphere. This "old" water at the end of the overturn of the lake still had a measurable tritium/helium-3 age. The age of 14 months is then interpreted as a result of mixing "old" and "young" water during the overturn (mixing age) and of helium-3 ingrow since then (true age). As the true age can be assumed 8 months (cf. age of the 25 m layer) the mixing age and thus the mixing ratio of "old" and "young" water in the deep water can be estimated: in order to explain the observed helium-3 age of 14 months a mixture of roughly 60% "young" and 40% "old" water has to be assumed at the end of the overturn of the lake. These figures are in accordance with the experimental oxygen data from Lake Constance which showed an increase of the oxygen concentration during the overturn of the lake in 1975/76 from 55% saturation to 85%.

III. Radon-222 study - vertical eddy mixing near the lake bottom

Radon-222 measurements in near bottom waters are suited to study vertical eddy mixing under natural conditions (BROECKER et al. 1968, IMBODEN a. EMERSON 1977). The method is based on the fact that radon-222 contained in sediments and dissolved in natural waters, in the vicinity of the sediment/water interface is found in excess to equilibrium with its parent nuclide radium-226 dissolved in the water. Large amounts of excess radon is then mixed away from the sediment/water interface before it undergoes radioactive decay (mean radioactive lifetime: 5.5 days). The mean height up to which excess radon is observed in the water depends on the intensity of vertical mixing.

Fig. 6 presents preliminary results for Lake Constance. Starting from values of about 70 cpm/100 l the observed excess α -count rates - 1 cpm α -count rate is roughly equivalent to a radon concentration of 0.5 dpm - show a pronounced decrease with height above bottom to reach a value of 10 cpm in 30 m height. A second measurement about 50 m above the bottom (about 7 m above the thermocline) gave almost the same concentration. It is therefore concluded that the value of 10 cpm/100 l corresponds to the radioactive equilibrium between radon-222 and its parent nuclide in the water (water samples for radium-226 determination have been collected, but are not yet analyzed). With a uniform vertical eddy diffusion coefficient D one expects an exponential decrease of the excess radon concentrations with height (BROECKER et al. 1968). Fig. 6 shows theoretical curves for D varying between 0.1 and 0.3 cm^2/sec , which reasonably fit the experimental data. It should be kept in mind, that in a lake, contrary to the situation in the open ocean, where the vertical distribution of excess radon indeed can be treated as a onedimensional problem, bottom geometry and lateral boundaries often cannot be neglected (cf. IMBODEN a. EMERSON 1977) so that one rather deals with a two or three dimensional mixing problem. The fine structure observed in the collected data may be due to this fact. Nevertheless the eddy diffusion coefficients obtained from the profile certainly give the right order of magnitude for the vertical mixing.

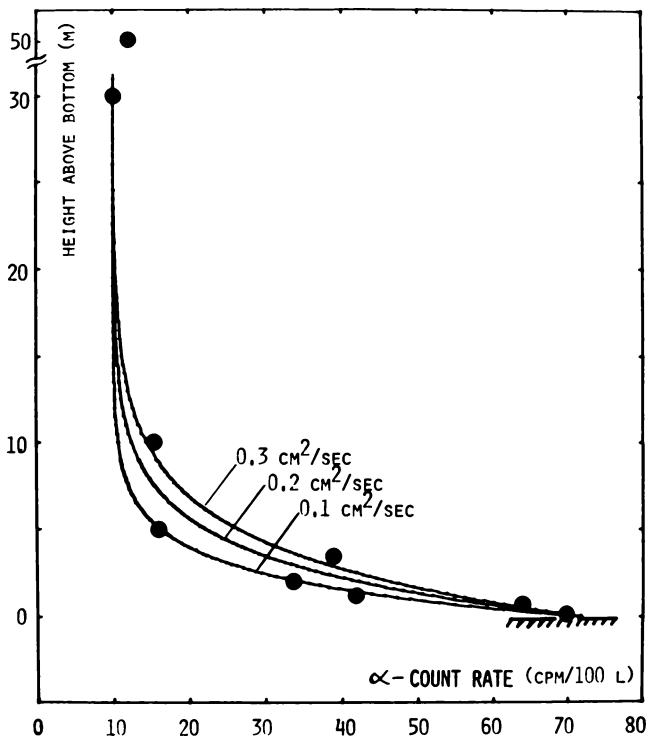


fig. 6: Vertical profile of excess radon-222 in Lake Constance.

(Sampling date 21. Sept. 77, sampling position: half way between Eichhorn and Bottinghofen, bottom depth: 62 m, depth of thermocline: 17 m). Gas samples were extracted from about 80 l of water. Statistical errors (1 sigma) are 3-5% (\approx 2 hours counting time). Radon concentrations are given in cpm/100 l (1 cpm \approx 0.5 dpm). Theoretical curves for model eddy diffusivities $D = 0.1$ to $0.3 \text{ cm}^2/\text{sec}$ are given according to a one dimensional model description of the mixing process: with $C(z) = C(0) e^{-z \sqrt{\lambda/D}}$ (λ = radon decay constant, z = height above bottom). Note the broken ordinate.

Field work will be continued in the future in order to achieve better understanding of the three dimensional mixing pattern of Lake Constance making use of a new ship-going radon detection system described by ROETHER and KROMER (1978). Mobility is one of the great advantages of this system which makes it superior to the detection system available so far. It is planned to further improve the present system by doubling the number of radon detection chambers and reduce the processing time for the water to one half of its present value. With this modification of the system we shall be able to analyze 8 radon samples in about 100 minutes with 3% precision, which will increase the present sensitivity of the radon method considerably.

IV. Summary

From the distribution of the environmental isotopes tritium, helium-3 and radon-222 in Lake Constance information is obtained about the renewal of the deep water of the lake, the vertical mixing of the lake water and the gas exchange with the atmosphere: From the tritium distribution in the lake between 1963 and 1974 the deep water renewal is calculated: about 15% of deep water mass have been renewed per year during the overturn of the lake, about 14% during the stagnation period. Gas exchange with the atmosphere during the overturn of the lake in winter 1976/77 was characterized by evasion rates for helium-3 between 2.2 and 3.9 m/d. From the distribution of excess radon-222 near the bottom of the lake a range of 0.1 to 0.3 cm²/sec was calculated for the vertical eddy diffusion coefficient.

"Gas exchange" and "internal mixing" describe a variety of physical processes, i.e., the rate of invasion or evasion of gases at the lake surface, gas renewal during overturn, vertical and horizontal eddy mixing and water renewal of a lake. A quantitative description of the physical mechanisms involved in these processes is the basis for an appropriate understanding of the dynamical behaviour of a lake and thus of its ecology. In the past the mechanisms have often been described qualitatively, the quantitative treatment, however, still lags behind considerably due to a lack of adequate methods. This paper summarizes the results of experimental work which has been carried out at Lake Constance. The project is continuing and it is the aim to develop methods which provide new information about these processes and the parameters governing them.

Our approach to the questions is to use the distribution of environmental isotopes, i.e., tritium, helium-3 and radon-222, in time and space, in order to "trace" water masses and to thus obtain information about the dynamics involved. It is hoped to apply the results obtained to other substances like CO₂, O₂, phosphate etc. to achieve better understanding of their budgets and thus of biological and chemical processes in the lake (cf. LEHN 1976, ELSTER 1975).

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