

Rapid deep-water renewal in Lake Issyk-Kul (Kyrgyzstan) indicated by transient tracers

Abstract—Simultaneous profiles of the transient tracers sulfur hexafluoride (SF_6), ^3H - ^3He , and the chlorofluorocarbons CFC-11 and CFC-12 were measured in Lake Issyk-Kul, a large, deep lake in Kyrgyzstan. Apparent water ages derived from these measurements suggest rapid mixing, with a deep-water renewal rate $>10\%$ yr^{-1} at 650 m depth. SF_6 and ^3H - ^3He ages agree reasonably well, whereas CFC ages are significantly greater. The discrepancy is explained by the nonlinear relationship between tracer age and tracer concentration and by the flattening of the atmospheric growth curves for CFCs. Novel to physical limnology is the application of SF_6 dating, which proves to be an excellent tool for the study of mixing in lakes, complementing ^3H - ^3He and CFC dating techniques.

Lake Issyk-Kul (Fig. 1) is located at an altitude of 1,606 m in the Tien Shan mountains of northeast Kyrgyzstan. With a water volume of 1,740 km^3 and a maximum depth of 668 m, Lake Issyk-Kul is one of the largest and deepest lakes in the world (Adyshev et al. 1987; Herdendorf 1990). The lake has no outflow and a refill time of ~ 330 yr. Precipitation over the lake surface is 277 mm yr^{-1} , and surface inflow corresponds to 568 mm yr^{-1} (Tsigelnaya 1995). The salinity (S) of the lake water is $\sim 6\text{‰}$ (the chemical composition is given by Tsigelnaya 1995 and Lyons et al. 2001). January mean air temperatures at the lake are below -2°C (Adyshev et al. 1987), but Lake Issyk-Kul never freezes completely. This is reflected in the Kyrgyz meaning of the lake's name—"warm lake." The lake is situated in a predominantly rural area with no major industries. Because of its unspoiled setting and its unpolluted water, Lake Issyk-Kul was a tourist attraction during the period of Soviet rule, and the Kyrgyz government is planning to invest in infrastructure improvements around the lake to establish a tourist industry that will serve as an important economic factor in the region. Because of concerns about the ecological impact not only of the tourist industry but also of potential contamination resulting from gold ore processing (a cyanide spill occurred in 1998) and from the possible leakage of radioactive waste from an abandoned uranium mine located near the southern shore of the lake, several research projects have been initiated to investigate the ecology of Lake Issyk-Kul. The lake is also a promising site for studying the paleoclimate of central Asia using sediment cores (Ricketts et al. 2001), the interpretation of which requires a detailed understanding of the lake's biogeochemistry and transport processes.

From 1978 to 1989, the Hydrometeorological Survey of the Soviet Union/Kyrgyzstan measured temperature, major ions, and nutrients at numerous stations in the top 200 m of the water column of Lake Issyk-Kul at intervals of at least 1 month. Similar data, sampled less frequently, are also available for the deep water. To complement this information, we provide data herein on the transient tracers ^3H , ^3He , sulfur hexafluoride (SF_6), and the chlorofluorocarbons CFC-

11 and CFC-12, which can be used to estimate deep-water residence times by use of dating techniques.

In limnology, the application of ^3H - ^3He dating (Torgersen et al. 1977, 1981; Aeschbach-Hertig et al. 1996; Hohmann et al. 1998) and dating by CFC-11 and CFC-12 (Weiss et al. 1991; Weiss and Volmer 1999; Peeters et al. 2000a; Aeschbach-Hertig et al. in press) is well established. The use of a combination of these tracers improves the reliability of the interpretation of the tracer concentrations in terms of mixing and deep-water residence times (Peeters et al. 1997, 2000a,b). On the basis of ^3H concentrations from 1976 (Romanov et al. 1989) and dissolved oxygen and conductivity-temperature-depth (CTD) data, Kipfer and Peeters (in press) have suggested that the residence time of the deep water of Lake Issyk-Kul can be expected to be <13 yr. Because the atmospheric input functions of CFC-11 and CFC-12 have increased only very slowly since 1996 (and, in the case of CFC-11, has even decreased over the past few years), errors in CFC dating applied to water masses younger than ~ 10 yr are large. Dating based on SF_6 concentrations has therefore been suggested as an alternative technique for the study of mixing in Lake Issyk-Kul (Kipfer and Peeters in press). The atmospheric concentration of SF_6 has increased rapidly since 1970, enabling reliable dating of waters with residence times between 0 and 30 yr. To our knowledge, this is the first study that has made use of SF_6 dating to study mixing in large lakes. In this note, we present and discuss our transient tracer data set from Lake Issyk-Kul and provide an estimate of the deep-water residence time.

Sampling—On 6 March 2001, the water column was sampled at the deepest point of Lake Issyk-Kul ($42^\circ 23.846'\text{N}$, $77^\circ 06.041'\text{E}$), approximately at the center of the lake (Fig. 1). Water samples were collected at 50-m depth intervals with 5-liter Niskin bottles. Via a silicon tube, water was filled into copper tubes and sealed gas-tight for the analysis of ^3H , ^3He , ^4He , Ne, CFC-11, and CFC-12. In addition, water was filled into 500-ml stainless-steel sampling cylinders (Whitey, 304L-HDF4-500; Arbor, Inc.) equipped with two plug valves (Nupro, SS-4P4T1; Arbor, Inc.) for the combined analysis of SF_6 and CFC-12. At the same time, a CTD profile was measured with a Seabird SB9 probe.

Analytical methods—Concentrations of ^3H , ^3He , ^4He , and Ne were measured according to the method of Beyerle et al. (2000). Because the measured ^3H concentrations did not vary significantly, only a subset of the samples was analyzed for ^3H , and for the calculation of the ^3H - ^3He water ages the ^3H concentrations were interpolated. The water samples collected in copper tubes for CFC-11 and CFC-12 analysis were measured according to the method of Hofer and Imboden (1998). Because the samples were measured within 80 d of sampling, no corrections for anaerobic CFC-11 depletion in the copper tubes were necessary. The error in the concen-

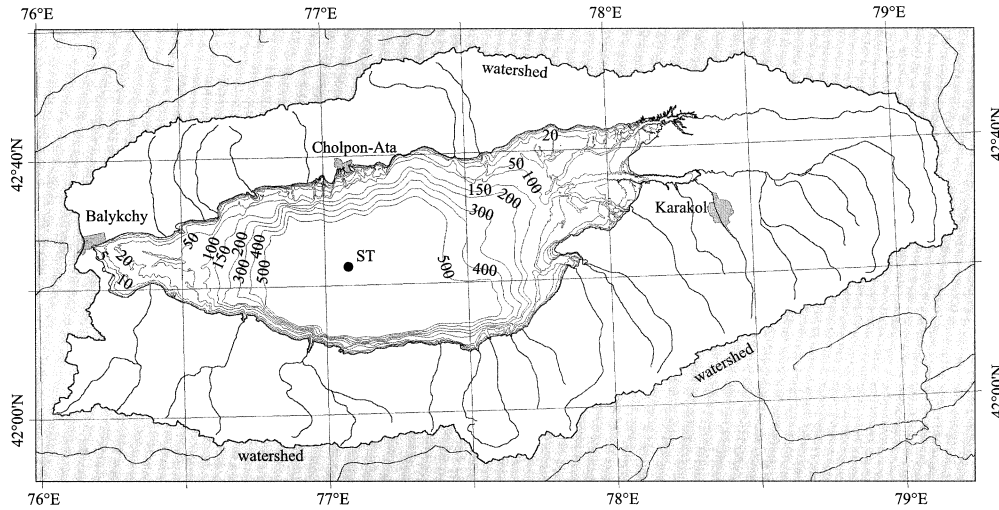


Fig. 1. Bathymetric map of Lake Issyk-Kul with its watershed. ST is the deepest station in the lake (650 m), from which all water samples were collected.

trations (at the 1σ level) is $\pm 5\%$ for both CFC-11 and CFC-12. Analogous to the measurement of CFC-11 and CFC-12, water samples collected in the 500-ml sampling cylinders were analyzed for SF_6 and CFC-12. Details on the new method will be published elsewhere, but, in brief, the gas was extracted from the samples in a vacuum line and frozen quantitatively on to an empty cold trap at -196°C , cooled by liquid nitrogen. After extraction, the trap was closed and heated to room temperature, and the water vapor removed in a small drying column filled with 3 Å molecular sieve. SF_6 and CFC-12 were separated in a gas chromatograph equipped with a 5 Å molecular sieve column (1.8 m \times 3.2 mm, 80/100 mesh, Alltech) and analyzed with an electron capture detector (ECD Fisons 800). In our gas chromatograph, H_2S elutes together with SF_6 , so that the SF_6 and H_2S peaks coincide. The presence of even trace amounts of H_2S therefore entirely masks the SF_6 peak. During the measurement series, it became apparent that this had occurred in three cases (see Table 1), which led us to include AgNO_3 powder in the drying column to remove H_2S prior to the gas analysis. After this measure had been introduced, no further problems with H_2S contamination occurred. The overall error of the method (1σ level) is $\pm 5\%$ for both SF_6 and CFC-12.

Dating techniques The ^3H - ^3He age, τ , can be calculated from Tolstikhin and Kamenskiy (1969) and Torgersen et al. (1979) as follows:

$$\tau = \frac{\tau_{1/2}}{\ln 2} \ln \left(1 + \frac{^3\text{He}_{\text{tri}}}{^3\text{H}} \right) \quad (1)$$

where $\tau_{1/2} = 4,500$ d is the half-life of ^3H (Lucas and Unterweger 2000) and $^3\text{He}_{\text{tri}}$ stands for tritogenic ^3He . $^3\text{He}_{\text{tri}}$ can be obtained from the ^3He : ^4He ratio and the ^3He and Ne concentrations as follows (e.g., Schlosser et al. 1989):

$$\begin{aligned} ^3\text{He}_{\text{tri}} = & ^4\text{He}_m(R_m - R_{\text{ter}}) - ^4\text{He}_{\text{eq}}(R_{\text{eq}} - R_{\text{ter}}) \\ & - L_{\text{ex}}(\text{Ne}_m - \text{Ne}_{\text{eq}})(R_{\text{ex}} - R_{\text{ter}}) \end{aligned} \quad (2)$$

where Ne and ^4He are used to correct for atmospheric and terrigenous contributions to the ^3He concentration. R denotes the ^3He : ^4He ratio, $L_{\text{ex}} = (\text{He}/\text{Ne})_{\text{ex}}$, and the indices indicate the measured (m) concentrations and ratios, the contribution from a terrigenous component (ter), from atmospheric equilibrium (eq), and from excess air (ex). As usual, with respect to noble gases, the excess air component is assumed to have the same composition as atmospheric air; hence, $L_{\text{ex}} = 0.288$. The terrigenous component is assumed to be purely radiogenic, with $R_{\text{ter}} = 2 \times 10^{-8}$, a typical value for the continental crust (Mamyrin and Tolstikhin 1984). The atmospheric equilibrium concentrations of ^3He , ^4He , and Ne were calculated by use of the empirical relationships of Benson and Krause (1980) and Weiss (1970, 1971).

The quasi conservative tracers SF_6 , CFC-11, and CFC-12 are manmade, and their atmospheric concentrations have increased since they were first produced. Dating based on these tracers compares the concentration in the water sample with the historic atmospheric equilibrium concentration of the tracer. The historic atmospheric equilibrium concentration is calculated from the atmospheric input function and the solubility of the gas at the temperature and salinity of the water sample and at the atmospheric pressure prevailing at the lake surface. The difference between sampling date and the apparent equilibration date gives the SF_6 , CFC-11, or CFC-12 age.

All of these tracer ages are a measure of the time elapsed since the water was last in contact with the atmosphere—that is, the isolation age. Note, however, that because historic atmospheric tracer concentrations and the ^3H input vary nonlinearly with time and ^3H - ^3He ages are a nonlinear function of ^3He and ^3H , the mixing of water masses leads to a discrepancy between tracer age and isolation age. Hence, tracer ages are often referred to as apparent water ages.

The above definition of tracer age implies that water masses with gas concentrations in equilibrium with the atmosphere have zero age. Note that the level of saturation of ^3He , SF_6 , and CFCs near the lake surface is a result of the

Table 1. Vertical profile of tracer concentrations in Lake Issyk-Kul, March 2001.

Depth (m)	Tritium* (TU)	$^3\text{He}\dagger$ (ccSTP g^{-1}) $\times 10^{14}$	$^4\text{He}\dagger$ (ccSTP g^{-1}) $\times 10^8$	Ne \dagger (ccSTP g^{-1}) $\times 10^7$	SF $_6$ \ddagger (pg kg^{-1})	CFC-11 \ddagger (pg kg^{-1})	CFC-12 \S (pg kg^{-1})	CFC-12 \parallel (pg kg^{-1})
10	11.7	5.60	3.88	1.67	—	770	350	340
50	—	5.59	3.86	1.66	—	780	330	340
100	11.6	5.97	3.90	1.72	0.249	—	330	340
150	—	6.24	3.91	1.67	—	790	330	310
200	11.7	6.38	3.86	1.69	0.216	—	320	—
250	—	6.70	3.90	1.66	0.193	—	300	—
300	11.1	6.88	3.90	1.69	0.182	790	280	330
350	—	7.23	4.01	1.70	0.174	740	290	—
400	11.0	7.29	3.88	1.68	0.167	760	310	310
450	—	7.41	3.94	1.68	0.162	780	300	330
500	11.7	7.37	4.01	1.76	0.168	800	300	300
550	—	7.19	3.96	1.70	0.190	770	280	310
600	—	7.44	3.92	1.69	0.155	700	290	280
650	11.6	7.68	4.12	1.74	0.141	670	280	280

* Measurement error ± 0.3 TU. \dagger Measurement error $\pm 1\%$. \ddagger Measurement error $\pm 5\%$. \S CFC-12 measurements from 500-ml sampling cylinders. Measurement error $\pm 5\%$. \parallel CFC-12 measurements from copper tube samplers. Measurement error $\pm 5\%$.All measurement errors given refer to the 1σ level.

interplay between deep-water mixing and limited gas exchange. As a consequence, the saturation level of the near-surface values is expected to vary seasonally, with the surface water temperature affecting the gas solubility (in particular that of SF $_6$ and CFCs) and the depth of the surface mixed layer affecting the flux of the tracer from deep-water regions. However, because deep-water renewal is expected to occur predominantly during the cold seasons, the near-surface apparent water age calculated from tracer data collected during seasonal mixing is considered to be a good

estimate of the reference age at the lake surface, which is relevant to deep-water renewal. Deep-water residence times are calculated from the difference between surface and deep-water tracer ages. If the atmospheric growth curves of the tracers are nonlinear, this technique is preferable to the commonly used method of altering tracer concentrations to obtain zero age at the surface (Peeters et al. 2000a).

If excess air is present, the apparent water age calculation outlined above has to be modified, because the excess air (introduced, for example, by the dissolution of air bubbles) acts as an additional source of the gaseous tracers in the water. This can be especially important in the case of SF $_6$ because of its poor solubility. Instead of comparing the tracer concentration in the water sample with the historic atmospheric equilibrium concentration, it should be compared to the historic concentration of the tracer in the water, C_{hist} :

$$C_{\text{hist}} = z_{\text{atm}} \left(\frac{P - p^*(T)}{P_o} L + A_{\text{ex}} \right) \quad (3)$$

where z_{atm} is the historic volume fraction of the gas in the atmosphere, P_o is the reference pressure, P is the atmospheric pressure, $p^*(T)$ is the saturation vapor pressure at temperature T (Gill 1982), L is the solubility at partial pressure P_o of dry gas, and A_{ex} is the concentration of excess air. The latter can be obtained from the excess of Ne above atmospheric equilibrium, ΔNe , because Ne is solely of atmospheric origin. In the case of Lake Issyk-Kul ($T \approx 4.5^\circ\text{C}$, $S \approx 6\%$, and $P \approx 0.813$ atm), 1% ΔNe corresponds approximately to $A_{\text{ex}} = 4 \times 10^{-6}$ mol air kg^{-1} of water. Because of the rural environment of the lake, contamination with SF $_6$ and CFCs due to industrial activities (Clark et al. 1995) is not expected to be significant.

The calculation of tracer ages requires historical atmo-

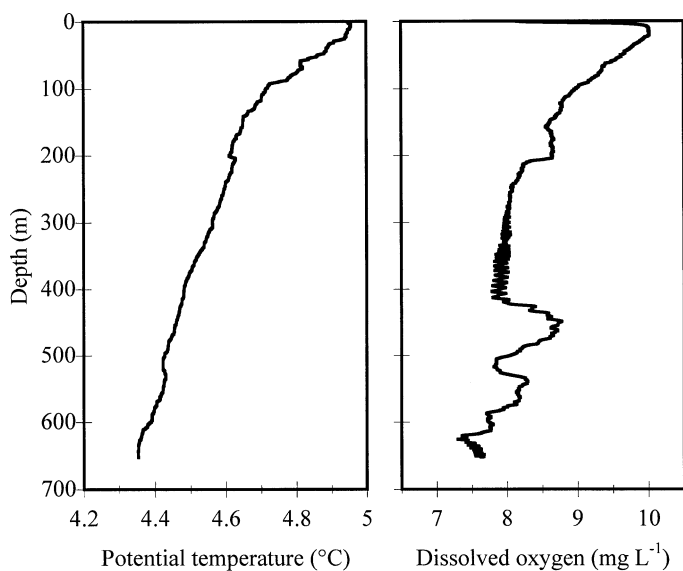


Fig. 2. Vertical profiles of temperature and dissolved oxygen measured on 6 March 2001 at the deepest station in Lake Issyk-Kul.

spheric concentrations and the tracer solubility. For the CFCs, we used the historical atmospheric concentrations of Walker et al. (2000) and the solubility functions of Warner and Weiss (1985). The latter were multiplied by $P_o/(P_o - p^*(T))$ to give the solubility of the dry gas. For SF₆, the atmospheric concentrations of Maiss and Brenninkmeijer (1998) were combined with a solubility function based on the coefficients of Wilhelm et al. (1976) and a correction term for salinity (Wanninkhof et al. 1991):

$$L_{\text{SF}_6} = \frac{1}{x_{\text{SF}_6} + C} \frac{\rho(T, 0)}{\rho(T, S)} \times 55.50868 \exp(-0.0117 \times S) \quad (4)$$

(mol kg⁻¹)

$$x_{\text{SF}_6} = \exp\{-[a1 + a2/T + a3 \ln(T)]/R\} \quad (5)$$

where x_{SF_6} is the Henry coefficient at the reference pressure P_o of 1 atm and ρ is the density function. In Eqs. 4 and 5, T is in K and S in g kg⁻¹. The parameter C accounts for the effect of gas partitioning on the total molar concentration of the solution. Because the molar concentration of tracer dissolved in the water is very small compared with the molar concentration of H₂O, $C \ll x_{\text{SF}_6}$, and C can be neglected. In the calculation of the Henry coefficient, the constants are $a1 = -877.854 \text{ cal K}^{-1} \text{ mol}^{-1}$, $a2 = 42,051 \text{ cal mol}^{-1}$, and $a3 = 125.018 \text{ cal K}^{-1} \text{ mol}^{-1}$ (Wilhelm et al. 1976), and the universal gas constant is $R = 1.98719 \text{ cal K}^{-1} \text{ mol}^{-1}$. Empirical equations published elsewhere for the solubility of SF₆ (Bullister et al. 2002) yield slightly larger values than those given by Eqs. 4 and 5; however, the difference is <3% for the temperature range (4–5°C) and salinity (6‰) of interest. When the solubilities of Bullister et al. (2002) are used, SF₆ ages result that are systematically lower than those obtained in this study by use of Eqs. 4 and 5, but only by ~0.3–0.4 yr.

Results and discussion—Figure 2 shows the vertical profiles of potential temperature and dissolved oxygen at the deepest station. Potential temperature decreases only slightly with increasing depth, from 4.95°C at the surface to 4.35°C at 650 m. This temperature profile is typical for March conditions. As mentioned above, Lake Issyk-Kul does not freeze. Most likely, this is the result of two effects: (1) salinity reduces the temperature of maximum density at the lake surface to ~2.6°C, which requires the surface water to cool to 2.6°C before the establishment of inverse stratification in winter; and (2) rapid mixing associated with surface-water cooling during winter mixes the cold surface water with deeper water that has a temperature that is typically >4°C.

In the deep water, dissolved oxygen decreases with increasing depth, which indicates oxygen consumption. However, even at 650 m depth, dissolved oxygen concentrations are still ~75% of the atmospheric equilibrium concentration at the lake surface (~10.0 mg L⁻¹ at $T \approx 4.5^\circ\text{C}$, $S \approx 6\text{‰}$, and $P \approx 0.813 \text{ atm}$). This indicates either that oxygen depletion rates are very low or that deep-water renewal, transporting dissolved oxygen from the surface to the depths of the lake, is fast.

Table 1 shows all measured concentrations of ³H, ³He,

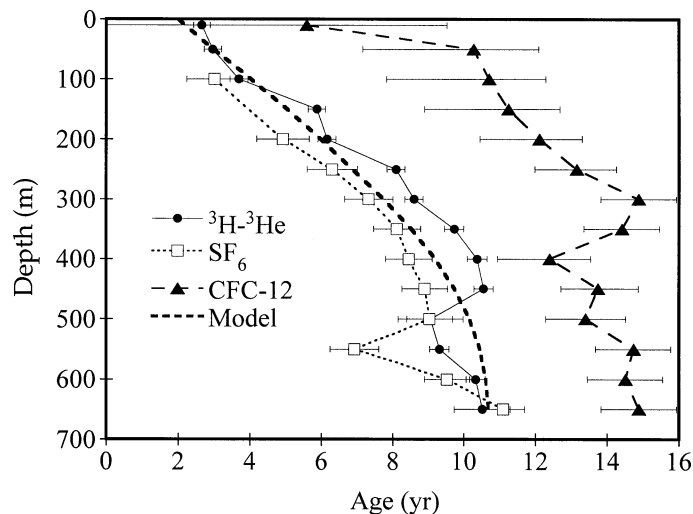


Fig. 3. Profiles of tracer ages calculated from the measured concentrations of ³H, ³He, SF₆, and CFC-12 at the deepest station in Lake Issyk-Kul. The decrease in the measured tracer ages between 400 and 600 m depth is correlated with an increase in dissolved oxygen in the same depth region (see Fig. 2). The thick dashed line shows the isolation age simulated by a simple mixing model that assumes that isolation age is at steady state and that vertical transport can be described analogously to Fick's Law with a diffusivity of $5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$.

⁴He, Ne, SF₆, CFC-11, and CFC-12. ³H concentrations are nearly homogeneous throughout the water column. ³H decay results in a decrease per unit of time of the ³H concentration in the water column. Rapid mixing could be an explanation for the homogeneous ³H profile. However, because the input of ³H into the lake also decreases with time, a homogeneous ³H profile does not necessarily imply rapid mixing.

⁴He concentrations (Table 1) are close to atmospheric equilibrium throughout the water column. The slight increase in ⁴He excess with depth is probably due to an influx of ⁴He from terrigenous sources.

Based on the tracer data from Table 1, ³H-³He, SF₆, CFC-11, and CFC-12 apparent water ages were calculated. The excess of Ne above atmospheric equilibrium is small for all samples, ranging from 0% to 5.5% ΔNe. As a consequence, the effect of the correction for excess air on the tracer age calculations is slight, increasing the apparent water ages by <0.7 yr in the case of SF₆ and 0.1 yr in the case of the CFCs.

³H-³He ages increase with depth (Fig. 3). This indicates that, although the water column is nearly homothermic, the lake is still not fully mixed. However, ³H-³He ages in the deep water are only ~11 yr, which suggests rapid deep-water renewal. The surface water has a ³H-³He age of ~2–3 yr. Apparently, gas exchange at the lake surface is not sufficiently fast to remove the ³He excess that is mixed rapidly upward from deeper in the water column. From the ³H-³He ages, the residence time of the deep water determined from the difference in apparent water ages is estimated to be <9 yr, which implies a deep-water renewal rate that is >10% yr⁻¹.

Although the SF₆ ages are ~1–2 yr less than the corre-

sponding ^3H - ^3He ages, the increase in SF_6 age with depth is very similar to that of ^3H - ^3He age. Hence, the deep-water residence time calculated from the difference in SF_6 ages is essentially the same as that obtained from ^3H - ^3He ages. CFC-11 and CFC-12 ages are ~ 4 – 5 yr greater than the corresponding ^3H - ^3He ages. The results from the two independent CFC-12 measurements agree to within measurement error. In Fig. 3, the large error bars near the surface result from the nearly flat atmospheric input functions for CFC-12, which makes dating difficult and imprecise. The CFC-11 ages (not shown in Fig. 3) agree reasonably well with the CFC-12 ages. However, the errors in the CFC-11 ages are very large because of the nearly constant atmospheric concentrations of CFC-11. As a consequence, in half of the cases, CFC-11 ages are not only compatible with the CFC-12 ages, they could also be interpreted as zero age, which indicates that CFC-11 dating is of very limited value not only for mixing studies in Lake Issyk-Kul but also in many other young bodies of water (e.g., groundwater or oceanic water masses).

The differences between the apparent water ages obtained from the different tracers can be explained by the nonlinear effect that mixing has on tracer age. The mixing of water volumes with different isolation ages should ideally give the volume-weighted mean isolation age—that is, the “true” isolation age. In the case of the tracer ages, however, mixing generates water containing a volume-weighted mean tracer concentration. Because the tracer age is, in general, a nonlinear function of tracer concentration, the tracer age of the mixed water can differ significantly from the true isolation age. The effect of mixing on tracer ages has been discussed for ^3H - ^3He ages in the ocean (Jenkins and Clarke 1976) and in Lake Baikal (Hohmann et al. 1998), and for CFC ages in the Caspian Sea (Peeters et al. 2000a) and in the ocean (Sonnerup 2001). It depends on the tracer used for dating, the date of sampling, and the typical water ages in the lake.

Figure 4 illustrates the effect of mixing on SF_6 , ^3H - ^3He , and CFC ages. If the atmospheric input function C_{atm} of a tracer is concave (see Fig. 4a)—that is, if $d^2C_{\text{atm}}/dt^2 > 0$, as is the case for SF_6 —the tracer age is younger than the true isolation age of the mixed water. However, if the atmospheric input function is convex (see Fig. 4b)—that is, if $d^2C_{\text{atm}}/dt^2 < 0$, as is the case for CFC-11 and CFC-12—the tracer age is older than the true isolation age of mixed water. The magnitude of this difference depends on the magnitude of d^2C_{atm}/dt^2 (Fig. 4a,b). Under the assumption of an exchange of $10\% \text{ yr}^{-1}$ of the deep water with water in atmospheric equilibrium, the difference of 4–5 yr between SF_6 and CFC ages at the maximum depth of Lake Issyk-Kul can be explained by an exponential mixing model of the type used in tracer hydrology (Maloszewski and Zuber 1982). The exponential mixing model as applied herein assumes that a fixed fraction of a mixed water volume is replaced per unit time by water having the tracer concentration corresponding to the actual tracer input c_{in} to the system, here to the atmospheric equilibrium concentration corrected for excess air:

$$\frac{dc(t)}{dt} = \alpha[c_{\text{in}}(t) - c(t)] \quad (6)$$

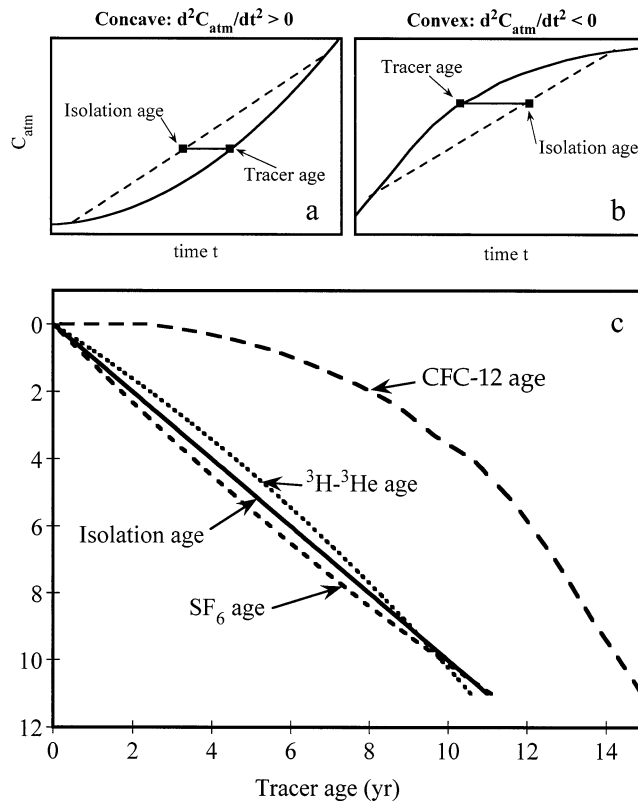


Fig. 4. The effect of mixing on tracer ages. Tracer age and isolation age for mixtures of tracers with (a) concave and (b) convex input functions. (c) Volume-weighted mean isolation age and tracer ages calculated for different mixtures of deep water (from 650 m depth) with water in contact with modern air at surface pressure having the same temperature, salinity, and concentration of excess air as the deep water. The isolation age was assumed to be 0 yr at the lake surface and 11 yr in the deep water (650 m).

where α is the fraction of the water volume exchanged per unit time.

Figure 4c compares the true isolation age and the tracer age of several mixtures of Issyk-Kul water from 650 m depth with water in contact with modern air at surface pressure ($P = 0.813 \text{ atm}$, $C_{\text{air},\text{SF}_6} = 5.127 \text{ pptV}$, $C_{\text{air},\text{CFC-11}} = 262.9 \text{ pptV}$, and $C_{\text{air},\text{CFC-12}} = 544.1 \text{ pptV}$) having the same temperature, salinity, and concentration of excess air as the deep water ($T = 4.3^\circ\text{C}$, $S = 6\text{‰}$, and $A_{\text{ex}} = 1.748 \times 10^{-5} \text{ mol kg}^{-1}$). Under the assumption that the SF_6 and ^3H - ^3He ages of ~ 11 yr at 650 m depth (Fig. 3) correspond to the true isolation age, the discrepancy between tracer age and true isolation age is < 0.6 yr in the case of the SF_6 dating method but up to 6.6 yr in the case of the CFC-12 dating method (Fig. 4c). For CFC-11 (not shown), the discrepancy is even greater (11.2 yr).

In the case of ^3H - ^3He dating, we used a similar approach to that used for SF_6 and CFCs by generating hypothetical mixtures of $^3\text{He}_{\text{tri}}$ measured at 650 m depth with $^3\text{He}_{\text{tri}} = 0$ (the expected value for water in contact with the atmosphere) and using the same ^3H concentration for all mixtures. The difference between isolation age and ^3H - ^3He age is caused by the logarithm in Eq. 1. The ^3H - ^3He water ages generally

exceed the isolation age because the second derivative of the ${}^3\text{H}$ - ${}^3\text{He}$ age with respect to ${}^3\text{He}_{\text{ini}}$ is negative. The discrepancy between isolation age and ${}^3\text{H}$ - ${}^3\text{He}$ age is <0.6 yr.

The discussion above demonstrates that, in Lake Issyk-Kul, tracer ages derived from SF_6 and ${}^3\text{H}$ - ${}^3\text{He}$ provide a more reliable estimate of the isolation age than those derived from CFC-12 or CFC-11. Because mixing leads to an underestimate of the isolation age in the case of SF_6 and to an overestimate in the case of ${}^3\text{H}$ - ${}^3\text{He}$, the isolation age should lie between the SF_6 and ${}^3\text{H}$ - ${}^3\text{He}$ ages. The close agreement between the SF_6 and ${}^3\text{H}$ - ${}^3\text{He}$ water ages severely constrains the possible range of values of the isolation age and thus provides additional support for the estimated deep-water renewal rate of $>10\%$ yr^{-1} .

A crude estimate of the vertical turbulent diffusion coefficient K_z in the deep water of Lake Issyk-Kul can be obtained by assuming that the SF_6 or ${}^3\text{H}$ - ${}^3\text{He}$ ages are at steady state and can be considered as the true isolation age, τ . In this case, the change in τ with z can be calculated from K_z and the morphometry of the lake:

$$\frac{d\tau}{dz} = -\frac{1}{K_z(z)} \frac{V(z)}{A(z)} \quad (7)$$

where z is the depth (positive upward), $A(z)$ is the cross-sectional area at depth z , and $V(z)$ is the volume of water below depth z . Equation 7 was derived from the volume-weighted balance of τ —that is, $-A(z)F(z) = d\tau/dt V(z)$, by treating τ as a tracer with a source term $d\tau/dt = 1$ yr yr^{-1} and assuming that the vertical flux F of τ is given by $F = -K_z d\tau/dz$. Under the assumption that $K_z = 5 \times 10^{-4}$ $\text{m}^2 \text{s}^{-1}$ independently of depth and time and that $\tau = 2$ yr at the lake surface, water ages modeled with Eq. 7 agree reasonably well with the measured SF_6 and ${}^3\text{H}$ - ${}^3\text{He}$ ages (Fig. 3). Hence, a value of K_z on the order of 5×10^{-4} $\text{m}^2 \text{s}^{-1}$ appears to be compatible with the tracer data. This value is of the same order as K_z estimated by inverse modeling from tracer data for the deep water of Lake Baikal (Peeters et al. 2000b). Note that the estimation of K_z from Eq. 7 assumes that vertical transport can be described by a local gradient law with a single diffusivity. In reality, variable wind forcing and seasonal changes in stratification cause vertical turbulent diffusivities to vary with time and depth. In addition, nonlocal mixing by intrusions may also play a significant role in Lake Issyk-Kul. Thus, an estimated diffusivity on the order of 5×10^{-4} $\text{m}^2 \text{s}^{-1}$ is a measure of the mean effect of mixing on tracer distributions rather than the true vertical turbulent diffusivity.

A more reliable and more precise quantification of deep-water mixing could be obtained by inverse numerical modeling of the different tracers. In this context, the information provided by the CFC concentrations may become useful by helping to constrain the parameters describing turbulent mixing in the water column and gas exchange at the lake surface. However, the development and application of a vertical transport model is beyond the scope of this note. Such a model would require a substantial amount of information on the mixing and transport processes involved, on the conditions limiting gas exchange at the lake surface, and on tracer inputs from the catchment, and this information is not yet available.

Markus Hofer,¹ Frank Peeters, Werner Aeschbach-Hertig, Matthias Brennwald, Johannes Holocher, and David M. Livingstone

Swiss Federal Institute of Technology (ETH) and Swiss Federal Institute of Environmental Science and Technology (EAWAG)
CH-8600 Dübendorf, Switzerland

Vladimir Romanovski

Institute of Water Problems and Hydropower of the National Academy of Sciences of the Kyrgyz Republic
720033 Bishkek, Kyrgyz Republic

Rolf Kipfer

Swiss Federal Institute of Technology (ETH) and Swiss Federal Institute of Environmental Science and Technology (EAWAG)
CH-8600 Dübendorf, Switzerland

References

- ADYSHEV, M. M. [ED.], AND OTHERS. 1987. Atlas of the Kyrgyz Republic, vol. 1: Natural conditions and resources (in Russian). Moscow. Glavnoe upravlenie Geodesii i Kartographii pri Sovjete Ministror USSR.
- AESCHBACH-HERTIG, W., M. HOFER, M. SCHMID, R. KIPFER, AND D. M. IMBODEN. In press. The physical structure and dynamics of a deep, meromictic crater lake (Lac Pavin, France). *Hydrobiologia*
- , R. KIPFER, M. HOFER, D. M. IMBODEN, AND H. BAUR. 1996. Density-driven exchange between the basins of Lake Lucerne (Switzerland) traced with the ${}^3\text{H}$ - ${}^3\text{He}$ method. *Limnol. Oceanogr.* **41**: 707–721.
- BENSON, B. B., AND D. KRAUSE. 1980. The concentration and isotopic fractionation of gases dissolved in freshwater in equilibrium with the atmosphere. 1. Oxygen. *Limnol. Oceanogr.* **25**: 662–671.
- BEYERLE, U., W. AESCHBACH-HERTIG, D. M. IMBODEN, H. BAUR, T. GRAF, AND R. KIPFER. 2000. A mass spectrometric system for the analysis of noble gases and tritium from water samples. *Environ. Sci. Technol.* **34**: 2042–2050.
- BULLISTER, J. L., D. P. WISEGARVER, AND F. A. MENZIA. 2002. The solubility of sulfur hexafluoride in water and seawater. *Deep-Sea Res. I* **49**: 175–187.
- CLARK, J. F., W. M. SMETHIE, AND H. J. SIMPSON. 1995. Chlorofluorocarbons in the Hudson Estuary during summer months. *Water Resour. Res.* **31**: 2553–2560.
- GILL, A. E. 1982. *Atmosphere-ocean dynamics*. Academic.
- HERDENDORF, C. E. 1990. Distribution of the world's large lakes,

¹ Corresponding author (markus.hofer@eawag.ch).

Acknowledgments

Thanks are due to Prof. Jan Klerkx; to our European, Russian, and Kyrgyz colleagues; to two anonymous reviewers, and to the crew of the *Moltur* for their excellent support and for the pleasant atmosphere that prevailed during the expedition. This research was made possible by funding from the Swiss Federal Office of Education and Science (contract 99.0720) within the framework of the European Union INCO/COPERNICUS Project APELIK (“Assessment and Prognosis of Environmental Changes in Lake Issyk-Kul [Kyrgyzstan]”; contract ICA2-CT-2000-10003).

- p. 3–38. In M. M. Tilzer, and C. Serruya [ed.], Large lakes: Ecological structure and function. Springer-Verlag.
- HOFER, M., AND D. M. IMBODEN. 1998. Simultaneous determination of CFC-11, CFC-12, N₂ and Ar in water. *Anal. Chem.* **70**: 724–729.
- HOHMANN, R., M. HOFER, R. KIPFER, F. PEETERS, AND D. M. IMBODEN. 1998. Distribution of helium and tritium in Lake Baikal. *J. Geophys. Res.* **103**: 12823–12838.
- JENKINS, W. J., AND W. B. CLARKE. 1976. Distribution of He-3 in Western Atlantic Ocean. *Deep-Sea Res.* **23**: 481–494.
- KIPFER, R., AND F. PEETERS. In press. Using transient conservative and environmental tracers to study water exchange in Lake Issyk-Kul. In J. Klerkx [ed.], The Issyk-Kul Lake: Evaluation of the environmental state and its remediation. NATO ASI Series. Series IV. Earth and Environmental Sciences. Kluwer.
- LUCAS, L. L., AND M. P. UNTERWEGER. 2000. Comprehensive review and critical evaluation of the half-life of tritium. *J. Res. Natl. Inst. Stand. Technol.* **105**: 541–549.
- LYONS, W. B., K. A. WELCH, J.-C. BONZONGO, E. Y. GRAHAM, G. SHABUNIN, H. E. GAUDETTE, AND R. J. PORETTA. 2001. A preliminary assessment of the geochemical dynamics of Issyk-Kul Lake, Kirghizstan. *Limnol. Oceanogr.* **46**: 713–718.
- MAISS, M., AND C. A. M. BRENNINKMEIJER. 1998. Atmospheric SF₆: Trends, sources, and prospects. *Environ. Sci. Technol.* **32**: 3077–3086.
- MALOSZEWSKI, P., AND A. ZUBER. 1982. Determining the turnover time of groundwater systems with the aid of environmental tracers. I. Models and their applicability. *J. Hydrol.* **57**: 207–231.
- MAMYRIN, B. A., AND I. N. TOLSTIKHIN. 1984. Helium isotopes in nature. Elsevier.
- PEETERS, F., AND OTHERS. 2000a. Analysis of deep-water exchange in the Caspian Sea based on environmental tracers. *Deep-Sea Res. I* **47**: 621–654.
- , M. HOFER, D. M. IMBODEN, AND V. M. DOMYSH-EVA. 2000b. Vertical turbulent diffusion and upwelling in Lake Baikal estimated by inverse modeling of transient tracers. *J. Geophys. Res.* **105**: 3451–3464, 14283.
- , R. HOHMANN, M. HOFER, D. M. IMBODEN, G. G. KODENEV, AND T. KHOZDER. 1997. Modelling transport rates in Lake Baikal: Gas exchange and deep-water renewal. *Env. Sci. Technol.* **31**: 2973–2982.
- RICKETTS, R. D., T. C. JOHNSON, E. T. BROWN, K. A. RASMUSSEN, AND V. V. ROMANOVSKY. 2001. The Holocene paleolimnology of Lake Issyk-Kul, Kyrgyzstan: Trace element and stable isotope composition of ostracodes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **176**: 207–227.
- ROMANOV, V., L. S. VLASOVA, A. V. MESKHETELI, AND L. V. SALNOVA. 1989. A tritium study of the formation of natural waters of Issykul basin (in Russian). *Vodnye Resursy* **4**: 82–94.
- SCHLOSSER, P., M. STUTE, C. SONNTAG, AND K. O. MÜNNICH. 1989. Tritogenic ³He in shallow groundwater. *Earth Planet. Sci. Lett.* **94**: 245–256.
- SONNERUP, R. E. 2001. On the relations among CFC derived water mass ages. *Geophysical Res. Lett.* **28**: 1739–1742.
- TOLSTIKHIN, I. N., AND I. L. KAMENSKIY. 1969. Determination of ground-water ages by the T-³He method. *Geochem. Int.* **6**: 810–811.
- TORGERSEN, T., W. B. CLARKE, AND W. J. JENKINS. 1979. The tritium/helium-3 method in hydrology, p. 917–930. In IAEA [ed.], Isotope hydrology 1978. IAEA.
- , D. E. HAMMOND, W. B. CLARKE, AND T.-H. PENG. 1981. Fayetteville, Green Lake, New York: ³H-³He water mass ages and secondary chemical structure. *Limnol. Oceanogr.* **26**: 110–122.
- , Z. TOP, W. B. CLARKE, W. J. JENKINS, AND W. S. BROECK-ER. 1977. A new method for physical limnology—tritium-helium-3 ages—results for Lakes Erie, Huron and Ontario. *Limnol. Oceanogr.* **22**: 181–193.
- TSIGELNAYA, I. D. 1995. Issyk-Kul Lake, p. 199–229. In A. F. Maudych [ed.], Enclosed seas and large lakes of Eastern Europe and Middle Asia. SPB.
- WALKER, S. J., R. F. WEISS, AND P. K. SALAMEH. 2000. Reconstructed histories of the annual mean atmospheric mole fractions for the halocarbons CFC-11, CFC-12, CFC-113, and carbon tetrachloride. *J. Geophys. Res.* **105**: 14285–14296.
- WANNINKHOF, R., J. R. LEDWELL, AND A. J. WATSON. 1991. Analysis of sulfur hexafluoride in seawater. *J. Geophys. Res.* **96**: 8733–8740.
- WARNER, M. J., AND R. F. WEISS. 1985. Solubilities of chlorofluorocarbons 11 and 12 in water and seawater. *Deep-Sea Res.* **32**: 1485–1497.
- WEISS, R. F. 1970. Helium isotope effect in solution in water and seawater. *Science* **168**: 247–248.
- . 1971. Solubility of helium and neon in water and seawater. *J. Chem. Engineering Data* **16**: 235–241.
- , E. C. CARMACK, AND V. M. KOROPALOV. 1991. Deep-water renewal and biological production in Lake Baikal. *Nature* **349**: 665–669.
- , AND M. VOLMER. 1999. A geochemical study of deep water renewal in Lake Malawi/Nyasa. *IDEAL Bull.* p. 10–11.
- WILHELM, E., R. BATTINO, AND R. J. WILCOCK. 1976. Low-pressure solubility of gases in liquid water. *Chem. Rev.* **77**: 219–262.

Received: 16 November 2001

Accepted: 4 April 2002

Amended: 8 April 2002