

## **Environmental Isotope Studies of an Alpine Snowpack**

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At the experimental plot of Weissfluhjoch in Switzerland, 2,540 m a.s.l., tritium, deuterium and oxygen-18 have been used to study exchange processes during the build-up and ablation of the snow cover as well as the hydrological balance. Selected results from the period 1971-1979 are presented. The varying isotope concentration of the respective snow layers reveal a mass exchange between the percolating melt water and the snowpack, influencing the isotope composition of the outflow from a snow lysimeter. A correlation between the isotope concentrations in the snow cover and meltwater has been established. The enrichment of meltwater in stable isotopes enables the evaporation to be calculated independently from the hydrological measurements. Parallel tritium data point to a surprisingly high exchange between the snow surface and air moisture.

### **Introduction**

In a previous study (Martinec et al. 1977) environmental isotopes have been used to study the hydrological balance and development of the snow cover of 1973 at Weissfluhjoch near Davos, Switzerland, 2,540 m a.s.l. In the following years, more data have been collected with the aim to confirm and expand these results whenever the isotopic and experimental conditions in a particular year offered such an opportunity. Several examples of these evaluations are presented in this paper. The study was again carried out in the framework of regular measurements of the snow cover accompanied by measuring the outflow of meltwater from a

snow lysimeter.

The environmental isotopes tritium ( $^3\text{H}$ ), deuterium ( $^2\text{H}$ ) and oxygen-18 ( $^{18}\text{O}$ ) were measured in samples taken from the precipitation, snow cover and meltwater. Tritium analyses were made by liquid scintillation counting, partially subsequent to electrolytic isotope enrichment. The results are given in  $TU$  with  $1 TU = 3.2$  Picocurie  $^3\text{H}$  in 1 liter of water. The measuring error (95% confidence level) is about 5 to 95  $TU$  depending on the tritium concentration and the enrichment factor used. Deuterium and oxygen-18, after sample preparation, are measured mass-spectrometrically. The results are given as relative deviations from an international standard water (V-SMOW)

$$\delta^2\text{H or } \delta^{18}\text{O} \equiv \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \cdot 1,000 \text{ ‰}$$

where  $R$  is the isotope ratio  $^2\text{H}/^1\text{H}$  or  $^{18}\text{O}/^{16}\text{O}$  for the sample or standard, respectively. The measuring error is  $\pm 1 \text{ ‰}$  for deuterium and  $\pm 0.2 \text{ ‰}$  for oxygen-18.

### Assessment of Tritium Data

The tritium content in precipitation comes mainly from nuclear weapon tests and decreases since 1963 where maximum values occurred in northern hemisphere precipitation. Superimposed are seasonal variations displaying relatively low tritium concentrations in winter precipitation and higher values in early summer precipitation. Since the early seventies short-term peaks of tritium concentrations in precipitation were found in agreement with other authors (for example Bauer et al. 1975, Weiss et al. 1979) which have to be ascribed mainly to tritium released from nuclear installations. Figs. 1 and 2 show a snowpack containing a layer (No.4) which was deposited in November 1974, with such an unusually high tritium content. Such a pronounced "natural" labelling of an individual snow layer helps in studying exchange processes during ablation. Fig. 2 shows the tritium content of the various snow layers at different times during the ablation period, together with the weighted means of the tritium concentrations of precipitation and lysimeter runoff within the indicated time intervals. When the snow ablation starts in April 1975, the tritium concentration in the underlying snow layers gradually increases. The same trend is observed in the samples from the lysimeter discharge (Fig. 3). The tritium content of the meltwater lies permanently above 200  $TU$  though the upper snow layer has mean tritium concentrations less than 200  $TU$ . This indicates that an isotope exchange occurs between the percolating melt water and the snow layer No. 4. Due to this exchange the meltwater reached a concentration of 400  $TU$  when this layer was melted in the middle of July. From

## Isotope Studies on a Snowpack

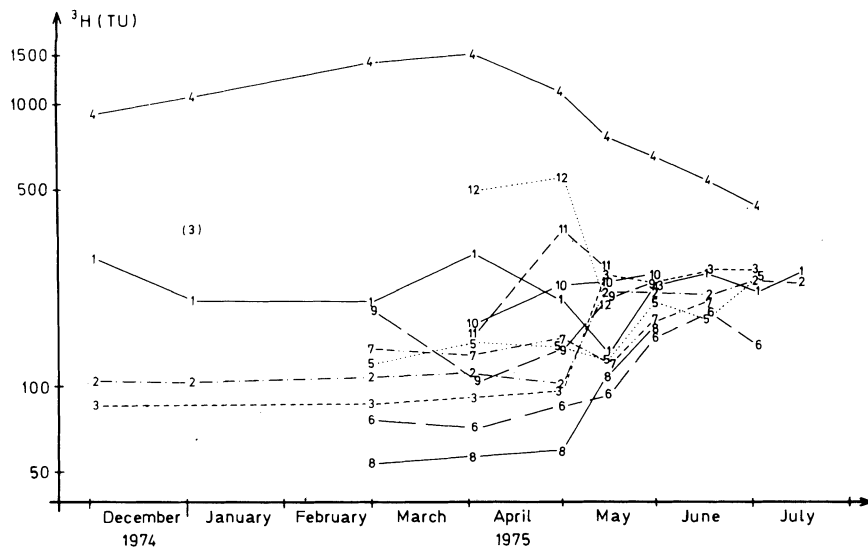


Fig. 1. Tritium concentrations of snow layers in the course of time. The figures indicate the sequence of the snow layers from the bottom towards the surface. The sample taken from snow layer No. 3 at the beginning of January 1975 has obviously been contaminated by snow from layer No. 4 during sampling.

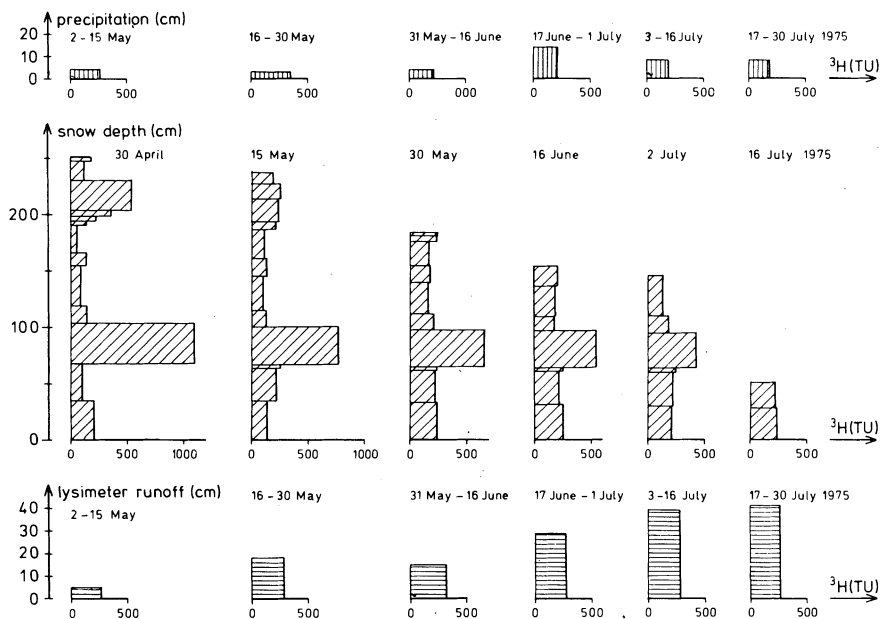


Fig. 2. Tritium in the precipitation, snowpack and lysimeter runoff during the ablation period.

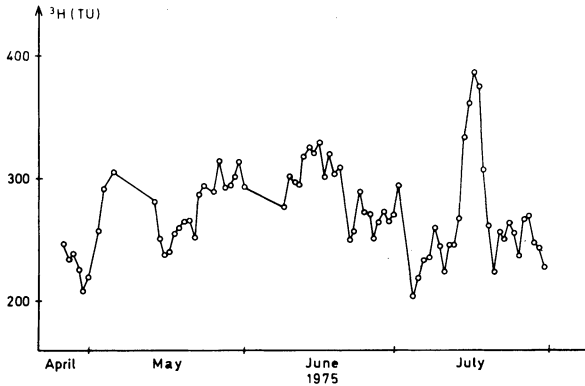


Fig. 3. Tritium concentrations in the outflow from the snow lysimeter.

the decrease in tritium content of this layer it can be roughly estimated that more than half of the water equivalent of this layer has been replaced by percolating water whilst the water equivalent of layer No. 4 was approximately constant between 30 March and 17 July.

### Assessment of Deuterium and Oxygen-18 Data

Labelling of precipitation by deuterium and oxygen-18 is due to the fact that its isotopic composition depends on temperature of condensation and evaporation, air moisture and origin of air masses. These effects lead generally to a seasonal variation of heavy isotope concentrations in precipitation with maximum values in summer and minimum values in winter. After deposition the isotopic content of snow can be changed by a temperature-dependent isotope fractionation during phase transitions.

#### a) Snowpack

As an example, Fig. 4 shows the labelling of different snow layers by their mean deuterium contents. It can be recognized that during the accumulation period the settling of the snow pack does not have any effect on the deuterium content of the individual layers. In the snow profile of 18 April 1977, the variation of isotope content in precipitation over the winter period, displaying a minimum in January precipitation, is being preserved, with a total variation range of about 100  $\delta$ -‰. At the begin of ablation (in May) the heavy isotope concentrations of the respective layers become more and more homogenized and enriched. As can be deduced from the variation of isotope distribution the melting takes place in the surface layer. The isotope content of the different layers does not change significantly during the accumulation period. Therefore it can be concluded that evaporation

## Isotope Studies on a Snowpack

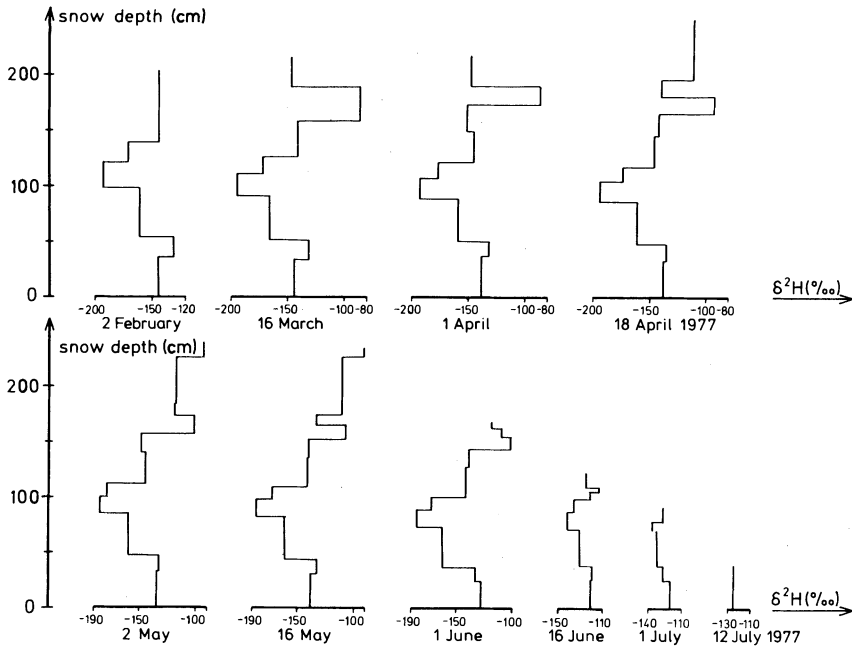


Fig. 4. Usual distribution of deuterium concentrations in a snow cover and its development in the course of time.

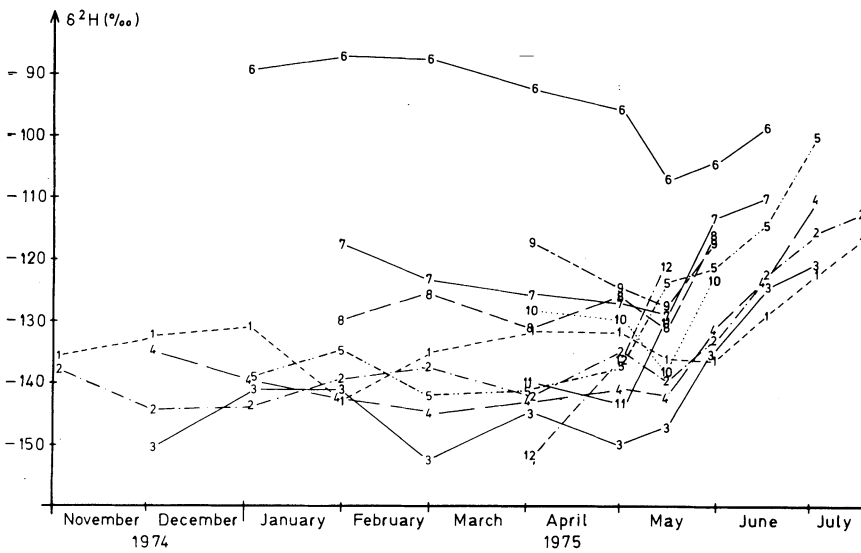


Fig. 5. Deuterium concentrations of snow layers in the course of time. The figures indicate the sequence of the snow layers from the bottom towards the surface.

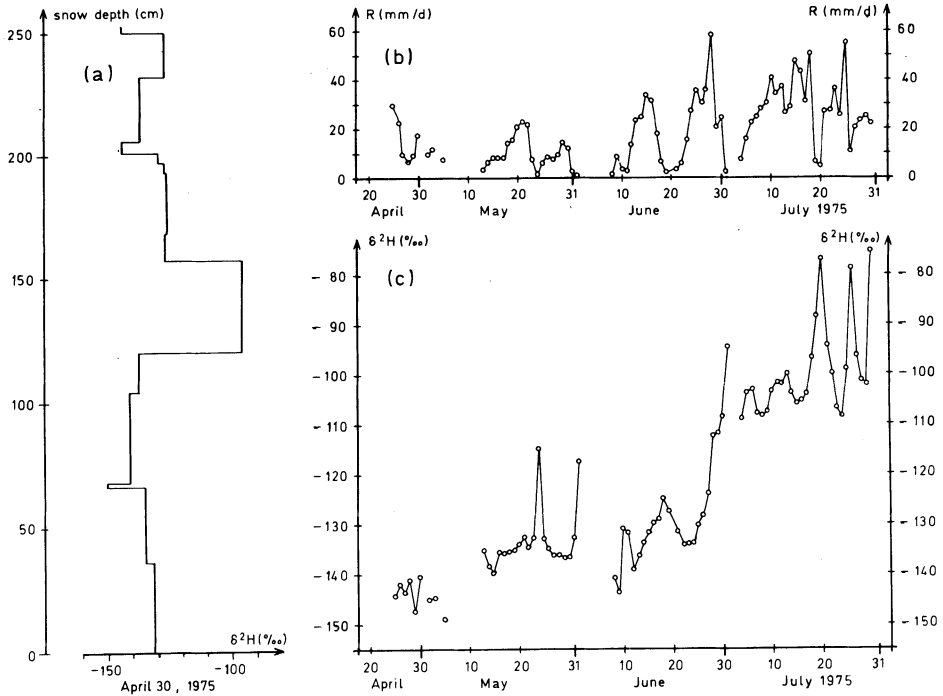


Fig. 6. Deuterium concentrations in the outflow from the snow lysimeter (c) together with the hydrograph (b), and in the snow cover (a) at the beginning of the snowmelt season.

and condensation processes in the snowpack play a minor part during accumulation.

In addition to tritium the deuterium and oxygen-18 content of the snowpack was measured between November 1974 and June 1975. The results of the deuterium measurements are shown in Fig. 5 for each layer as a function of time. Compared to Fig. 4, the deuterium concentrations vary within a smaller range of about 30  $\delta$ -‰, with the exception of layer No. 6 which has an unusually high deuterium content with regard to the date of deposition at the end of December. This can be explained by the relatively high mean air temperature of  $-2.5^\circ\text{C}$  during the deposition of this layer whilst, e.g., the neighboured layers No. 5 and No. 7 were deposited at a mean air temperature of about  $-8^\circ\text{C}$  (Winterbericht EISLF 1976). From the begin of ablation in the middle of May, besides homogenization, all layers are enriched in deuterium due to melting and evaporation.

#### b) Lysimeter Runoff

When a snow pack melts it is to be expected that, due to isotopic fractionation, the light isotopes will prevail in the initial runoff followed by a steady increase of

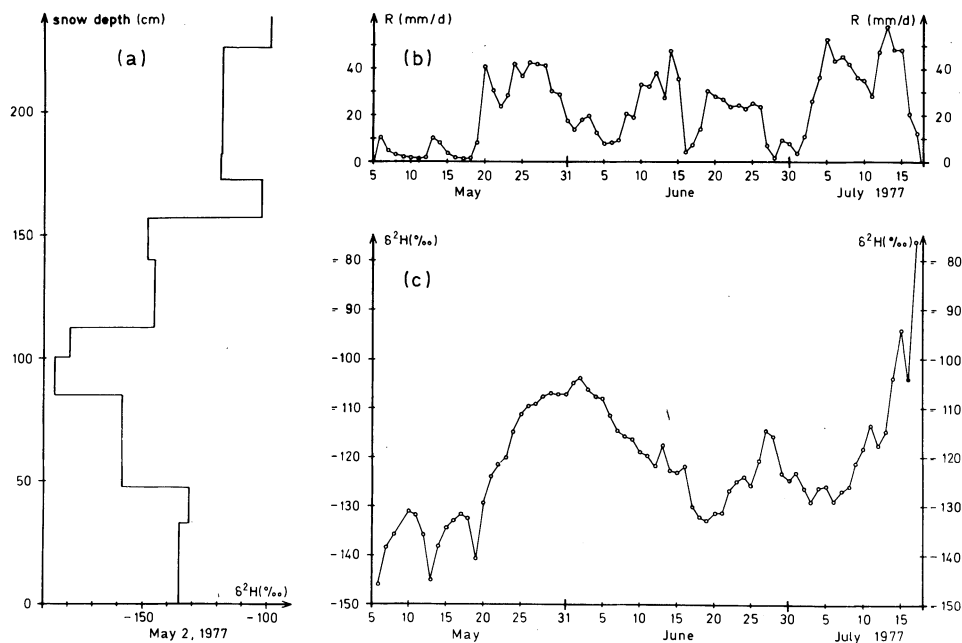


Fig. 7. Deuterium concentrations in the outflow from the snow lysimeter (c) together with the hydrograph (b), and in the snow cover (a) at the beginning of the snowmelt season (from Herrmann et al. 1978).

heavy isotope content in the course of ablation. This has been verified by laboratory experiments carried out, for example, by Arnason 1969 and Herrmann et al. 1981. Corresponding results of field investigations are shown in Figs. 6 and 7. In Fig. 6a the isotope content of the snowpack is, with the exception of one layer, approximately constant with depth ( $\delta^2\text{H} \approx -129\text{‰}$ ). Consequently the isotope content of the lysimeter runoff shows a general increase from  $\delta^2\text{H}$  values of about  $-140$  to  $-100\text{‰}$ , disregarding some short-time peak values. Deviations of the measured isotope concentrations from the theoretically expected trend can be ascribed to the variation of the isotope content of different snow layers actually melting, and to isotope exchange of the percolating melt water and the snowpack. The mentioned short-term peak concentrations occur whenever melting ceases thus reflecting the long-time trend of the isotope content.

Fig. 7 shows a further example for the correlation of the isotope contents in the snowpack and the meltwater. In this case the heavy-isotope enrichment generally observed in the meltwater during the ablation period, as well as the short-time variations (Fig. 7c) are overshadowed by the differences of the isotopic composition of the snow layers melting successively.

## Hydrological and Isotopic Balance of the Snow Cover

The hydrological water balance is given by

$$R = W + P - E + C \quad (1)$$

where

- $R$  – total runoff depth (cm)
- $W$  – water equivalent of snow at begin of ablation (cm)
- $P$  – precipitation during ablation (cm)
- $E$  – evaporation during ablation (cm)
- $C$  – condensation of water vapor on snow surface during ablation (cm)

By comparing the stable isotope concentrations of  $R$  and  $W + P$ , the loss ( $-E + C$ ) can be estimated from the isotope fractionation effect of the evaporation. The maximum possible value of loss can be calculated using the Rayleigh formula for distillation at equilibrium conditions. After expressing the isotope ratios by the pertinent  $\delta$  values, the formula reads as follows

$$(\delta_R + 1,000) = (\delta_{W+P} + 1,000) f^{1/\alpha - 1} \quad (2)$$

where  $\delta_R$  and  $\delta_{W+P}$  are the  $\delta^{2H}$  or  $\delta^{18O}$  values of the components  $R$  and  $W + P$ ,  $f$  the fraction of  $W + P$  remaining after evaporation, and  $\alpha$  the isotope fractionation factor taken from literature ( $\alpha(^{2H}) = 1.132$  from Merlivat and Nief 1967;  $\alpha(^{18O}) = 1.01423$  derived from data given in Kuhn and Thürkauf 1958 and O'Neil 1968).

In order to obtain a better estimate of the loss an attempt was made to take into account the relative humidity and the isotope content of air moisture. According to Craig and Gordon (1965) the following equation can be derived

$$(\delta_R + 1,000) = \frac{1}{\alpha} \{ f^\alpha [ (\delta_{W+P} + 1,000) \alpha - (\delta_A + 1,000) b ] + (\delta_A + 1,000) b \} \quad (3)$$

where

$$\alpha = \frac{1/\alpha^* - (1-h)}{1-h} \quad \text{and} \quad b = \frac{h}{1-h}$$

with  $\alpha^* = \alpha \cdot \alpha_K$  and

- $\delta_A$  –  $\delta$  value of air moisture
- $\alpha_K$  – kinetic fractionation factor
- $h$  – relative humidity

For calculating the relative losses,  $1-f$ , from Eq. (3), the measured values of  $\delta_R$ ,  $\delta_{W+P}$ , and  $\delta_A$  were used together with the mean values of  $h$  taken from the pertinent winter reports (Winterberichte des EISLF 1974-1980) and  $\alpha^*$  obtained from laboratory experiments ( $\alpha_K(^{2H}) = 1.020$  and  $\alpha_K(^{18O}) = 1.0065$ , from



*Isotope Studies on a Snowpack*

Table 1 – Hydrological and isotope balance of the snow cover: calculated losses

	1973	1974	1975	1978	1979
Observation Period	17 May-28 June	17 May-16 July	1 May-30 July	17 July-8 August	15 June-19 July
Water equivalent of the snow cover [cm]	80.7	111.0	112.1	66.2	
Precipitation during the melting period [cm]	12.6	40.2	36.5	9.8	
Lysimeter runoff [cm]	88.1	143.5	144.3	73.3	
Hydrological Balance	6%	5%	3%	4%	*
Isotope Balance (max. values)					
<sup>2</sup> H	9%	8%	5%	1%	6%
<sup>18</sup> O	10%	9%	7%	1%	4%
Isotope Balance (taking air moisture into account)					
<sup>2</sup> H	5%	5%	2%	0%	2%
<sup>18</sup> O	5%	5%	6%	1%	1%

\* A hydrological balance in 1979 was not possible in view of the flooding of the test area by intensive snowmelt from the neighbouring slopes. An isotopic balance was however calculated because the lowest snow layer did not considerably affect the results.

Stichler 1981). The results together with the hydrological balance are given in Table 1. The mean isotope concentrations of  $W+P$ ,  $R$ , and  $P$  are listed in Table 2. It should be noted that an increase of tritium concentration resulted in the runoff when the tritium concentration of precipitation was higher than that of the snowpack. In 1975 for once it was lower and so was the tritium concentration of runoff. Therefore the changes cannot be explained only by isotopic fractionation due to evaporation. If one assumes exchange between the snowsurface and the air moisture to be the dominant process, the differences in tritium concentration point to a relative exchange rate,  $1-f^*$ , of about 0.10 to 0.25, under the assumption that the air moisture has the same tritium concentration as the precipitation, and using for calculation the simple mixing equation

$$T_R = f^* T_{W+P} + (1 - f^*) T_P \quad (4)$$

$T$  – tritium concentration referring to  $R$ ,  $W+P$ , and  $P$  (see Eq. (1))

$f^*$  – fraction of not-exchanged water equivalent

Table 2 – Mean isotope concentrations used for the isotope balance of the snow cover

	Mean deuterium and <sup>18</sup> O concentrations					
	Precipitation		Snow cover + precipitation		Lysimeter runoff	
	δ <sup>2</sup> H[‰]	δ <sup>18</sup> O[‰]	δ <sup>2</sup> H[‰]	δ <sup>18</sup> O[‰]	δ <sup>2</sup> H[‰]	δ <sup>18</sup> O[‰]
1973	- 69.0	- 10.04	- 118.5	- 16.27	- 108.5	- 44.88
1974	- 78.3	- 11.42	- 111.3	- 15.30	- 103.1	- 14.21
1975	- 81.0	- 13.35	- 117.2	- 16.46	- 114.7	- 15.41
1978	- 59.5	- 9.00	- 103.1	- 14.15	- 102.2	- 14.03
1979	- 92.3	- 12.57	- 114.8	- 15.43	- 108.7	- 14.85

	Mean tritium concentrations		
	Precipitation	Snow cover + precipitation	Lysimeter runoff
	[TU]	[TU]	[TU]
1971	312*	161*	180*
1973	176	104	123
1974	264	135	161
1975	213	289	276

\* From Arnason et al. (1973)

## Conclusions

Environmental isotopes provide a better insight into the mass exchange between the meltwater and snow and between the snow layers.

The enrichment of meltwater in heavy stable isotopes in comparison with the snow cover and precipitation is used to calculate the evaporation independently from hydrological measurements. In addition, tritium data point to a new aspect of the hydrological balance consisting in a strong mass exchange by evaporation and condensation at the snow surface.

A better knowledge of the mentioned processes improves the reliability of tritium, deuterium and oxygen-18 when used as tracers in hydrological studies on a basin scale.

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