Movement of water through snow pack traced by deuterium and tritium

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ABSTRACT: Environmental isotopes provide a valuable tool for a better understanding of the movement of water in snowpacks and in temperate glaciers. Depths and densities of the alpine snow cover were determined for the respective layers during two consecutive winter seasons. Snowmelt was continuously recorded by a snow lysimeter and the water balance of the experiment was established. Deuterium and tritium concentrations in precipitation, snowpack and meltwater have been measured in order to trace the movement of water, recrystallization and isotopic exchange in the snowpack. The theoretical model of this process was generally confirmed by the results.

RESUME: Les isotopes peuvent être très utiles pour mieux comprendre l'écoulement des eaux dans les couches de neige et dans les glaciers tempérés. Pendant deux hivers consécutifs, les hauteurs et les densités des neiges alpines ont été déterminées pour les couches respectives. Les eaux de fonte ont été enregistrées continuement par un lysimètre à neige et le bilan a été calculé. Les teneurs en deutérium et en tritium des précipitations, de la neige et de l'eau de fonte ont été mesurées pour pouvoir suivre le mouvement de l'eau, la recristallisation et l'échange isotopique dans la couche de neige. En général, les résultats confirment le modèle théorique de ce processus.

1. INTRODUCTION

During the last decade the isotopic composition of temperate glaciers and of snowpacks have been studied by several investigators. Examples are given in references [1-6]. Little or no isotope exchange between the percolating water and snow or ice was believed to take place at first. Later studies have shown that this assumption was not correct [7]. A theoretical model was designed [8] describing quantitatively the exchange process in the melting snow column. A good agreement was obtained between this theory and a laboratory experiment.

A study of the alpine snow cover with measurements of precipitation and snowmelt provided an opportunity to investigate the movement of water and the exchange process on a larger scale and under natural conditions. Results presented in this ˈpaper are based on experimental material obtained in winter seasons 1969-70 and 1970-71.

2. STUDY OF THE SNOW COVER

Figure 1 shows the development of snow cover in the experimental plot at Weissfluhjoch (2540 m asl) in Switzerland. The depth, density, and further properties of the respective snow layers are measured in regular intervals throughout the whole season; these data are published in year books of the Federal Institute for Snow and Avalanche Research [9].

Starting by April, snow samples have been taken from the layers of snow columns (Cl - CN in Fig. 1) for deuterium and tritium analysis. Identification of layers in consecutive samplings was ensured by coloured ribbons. Simultaneously, precipitation was measured by a heated recording rain gauge. In 1971, composite precipitation samples were also collected for isotope analysis during periods coinciding with the snow sampling.

3. MEASUREMENTS ON A SNOW LYSIMETER

A snow lysimeter with a surface area of 5.2 m^2, shown in Figure 2, served for determining the amount of water leaving the snow cover each day. This drain water was collected at 24-hr intervals and representative samples were taken for deuterium and tritium analysis. The water balance should correspond to the equation

$$W_b - W_e + P - E = D$$

where W_b, W_e are water equivalents of the snowpack at the beginning and at the end of the given period,

P is the precipitation,

E is the evaporation,

D is the amount of drain water.

In June, 1970, extreme snow depths and high temperatures caused the flooding of the experimental plot and meltwater from the vicinity may have penetrated into the lysimeter. This additional drain water was disregarded in a rough estimate. The following total values were thus obtained from 15 May to 30 July:

$$W_b - W_e = 1240.1 \text{ mm } (W_e = 0)$$
$$P = 243.8 \text{ mm} \qquad D = 1417.5 \text{ mm}$$

The difference between the available water and the outflow seems to account for the evaporation, which could not be directly measured. In 1971, the function of the lysimeter was improved and measurements obtained from 1 April to 10 July were:

$$W_b - W_e = 690.3 \text{ mm } (W_e = 0)$$
$$P = 301.2 \text{ mm} \qquad D = 960.7 \text{ mm}$$

This acceptable balance can still contain errors from the following main sources:

a) Inaccuracy of precipitation measurements;
b) variability of snow depths on the lysimeter and at the site of snow profiles (distance 20 m);

c) variability of snow depths between consecutive snow
profiles.

The scope of this paper does not allow a consideration of these
possible discrepancies in detail. It is probable that they affected
the numerical interpretation of isotope data and contributed to the
scatter of results.

4. DEUTERIUM MEASUREMENTS

Results measured at the University of Iceland are expressed as
the relative deviation δ from the standard mean ocean water (SMOW)
in $°/_{oo}$. The standard deviation of a sample was 1 $°/_{oo}$. Deuterium
measurements are shown in Figures 3 and 4. Snow columns are indi-
cated by C and are successively numbered. Samples of drain water
are indicated by D and of precipitation by P, with numbers referring
to the respective melting periods. The isotopic composition of
drain water is always plotted below the snow column sampled at the
end of the melting period, and the value for precipitation above the
snow column sampled at the beginning of the respective melting
period.
As the melting season proceeds, snow columns become enriched in
deuterium and fluctuations in the deuterium content of the respec-
tive layers are smoothed out. In Experiment 1970, however, the
column C3 has a lower mean deuterium concentration than C2. This
can be explained by the fact that the top layer of C2 which was very
rich in deuterium has melted away and percolated through the snow
without reaching isotopic equilibrium between the solid and liquid
phase. Tritium measurements give the same result. A similar
process is revealed by high deuterium concentrations in D1 and D2.
In all other cases drain water is depleted in deuterium in compar-
ison with the remaining snow. In Experiment 1971 the first drain
water samples have the lowest values and the deuterium concentration
increases continuously during the melting season despite the upper-
most and lowest layers of the original column having the highest
deuterium concentration.

5. TRITIUM MEASUREMENTS

Results which have been measured at the University of Iceland
are given in tritium units (T.U.) and are shown in Figure 5. C, D,
and P with successive numbers have the same meaning as in Figures 3
and 4. The standard deviation of a sample was about 6 per cent. In
Experiment 1970 the snow clearly reflects a part of the annual vari-
ation in the tritium concentration in precipitation. The early
winter minimum can be seen 35-60 cm above the bottom. Above that
the tritium concentration increases continuously.
Figure 5 shows qualitatively the result of the exchange between
snow and meltwater. The column is enriched in tritium as the
tritium-rich upper layers melt and percolate through the snowpack.
On certain days in June 1970 the drain water was richer in tritium
than any of the layers: Snowmelt was accompanied by rain which had
in June an average of 407 T.U. Mixed values calculated for the
drain water indicate that this rain water appeared within 24 hours
in the outflow together with meltwater after penetrating the snowpack.

6. LEAST SQUARE ADJUSTMENT OF EXPERIMENTAL DATA

We will consider a general case where N snow columns are sampled and samples are collected from precipitation and drain water in the subsequent N periods. To examine the consistency of the experimental data we have the following equations of conservation:

a) Conservation of water equivalence:

$$C1 + P1 = C2 + D1$$
$$\vdots$$
$$CN + PN = \qquad DN$$

b) Conservation of deuterium:

$$C1 \cdot \delta_{C1} + P1 \cdot \delta_{P1} = C2 \cdot \delta_{C2} + D1 \cdot \delta_{D1}$$
$$\vdots$$
$$CN \cdot \delta_{CN} + PN \cdot \delta_{PN} = \qquad DN \cdot \delta_{DN}$$

c) Conservation of tritium:

$$C1 \cdot T_{C1} + P1 \cdot T_{P1} = C2 \cdot T_{C2} + D1 \cdot T_{D1}$$
$$\vdots$$
$$CN \cdot T_{CN} + PN \cdot T_{PN} = \qquad DN \cdot T_{DN}$$

Experiment 1970

In Experiment 1970 N is equal to 5. As the measurements of tritium are not considered, ten equations emerge. Least square adjustment of experimental data was performed. The probable relative error of water quantities is expected to be about ten times the probable relative error of deuterium. This was implemented by an appropriate choice of weights. The experimental results and corrections are presented in Table 1. Since the values of P1, δ_{P1}, .. δ_{P5} were not measured, approximate values were selected (indicated by stars in the table).

Experiment 1971

More complete measurements were performed on samples from the second experiment. Both deuterium and tritium were measured. Seven snow columns were sampled and precipitation and drain water samples collected in the seven respective subsequent periods. For this set of data the number of equations of conservation becomes twenty-one. Unfortunately a program for a computer solving twenty-one linear equations with twenty-one unknown quantities was not available at the Computing Center of the University of Iceland. So it was necessary to perform the least squares adjustment separately for each isotope (involving only fourteen linear equations with fourteen unknown quantities each time). Mean values of corrections for water equivalents obtained in each case are used for further computations.

The quantities and corrections involved are presented in Table 1. Approximate values were selected when data were not available (indicated by stars in the table). As before the relative error of tritium was adjusted to effect similar correction of water quantities as was the case for deuterium. This mechanical adjustment of data is not quite satisfactory especially concerning the water equivalents of snow columns. The corrections do not always correspond to actual conditions on the site.

Table 1

Least square adjustment of experimental data for water equivalent, deuterium, and tritium. The uppermost figure in each square is the measured value. The second figure is correction obtained from deuterium data. The third figure is correction obtained from tritium data. Values indicated by stars are approximate values. As adjusted water equivalents, mean values are used, obtained from data for tritium and deuterium respectively. Water equivalents are in cm.

		Snow column			Precipitation			Drain water		
		Water equiv	$-\delta\%_o$	TU	Water equiv	$-\delta\%_o$	TU	Water equiv	$-\delta\%_o$	TU
Experiment 1970	1	97.6 -0.5	143.5 0.8		32.9* -2.8	75.9* 0.7		12.4 0.1	127.1 -0.1	
	2	126.0 -11.4	130.2 -1.6		3.5 0.0	75.9* -0.1		16.0 0.0	110.0 0.1	
	3	107.1 -5.0	138.0 -8.1		4.5 0.5	75.9* -1.1		43.8 -0.3	130.1 3.2	
	4	66.7 -3.1	119.8 2.7		4.6 0.2	75.9* -0.4		54.6 -1.6	119.0 1.1	
	5	16.2 -0.9	114.1 2.1		1.6 -0.1	75.9* 0.8		17.8 -1.0	114.9 -2.0	
Experiment 1971	1	69.0 -14.9 -13.5	133.9 -4.5	104 -7	0.2 0.0 0.0	125.0* 0.0	280 -2	1.2 0.0 0.0	135.3 0.1	206 5
	2	65.5 -12.4 -10.9	132.6 -3.8	85 7	4.8 0.7 1.1	120.0* -0.5	280 16	0.6 0.0 0.0	143.0 0.1	160 -1
	3	64.1 -6.1 -4.4	127.2 -0.2	105 6	1.6 -0.7 0.8	160.0 -0.3	368 3	10.5 1.5 0.3	141.5 1.5	116 -18
	4	55.1 -8.2 -3.7	123.5 0.0	150 -22	6.9 -1.6 -3.3	123.5 -0.8	322 -3	15.1 1.7 -0.3	129.4 1.8	143 14
	5	40.8 -5.4 -0.7	122.0 -1.9	131 1	8.9 0.9 -4.9	115.5 -1.2	414 -4	13.3 1.0 0.1	122.0 2.0	210 16
	6	34.2 -3.2 -3.5	111.2 4.6	123 4	11.1 2.0 2.8	84.4 0.0	212 2	31.2 -2.8 -2.5	111.4 -0.1	217 -61
	7	14.1 1.6 1.8	99.3 -0.4	162 -2	2.5 0.3 0.4	122.3 0.0	341 -1	24.2 -5.7 -5.4	101.5 0.7	170 13

7. EQUATIONS OF ISOTOPE FRACTIONATION BETWEEN ICE AND WATER IN MELTING SNOW COLUMN

The data obtained in the present experiment offer an excellent opportunity to test the validity of theoretical equations of isotope fractionation [8]. These equations are a pair of linear first order partial differential equations:

$$\frac{\partial u}{\partial t} + K\frac{\partial u}{\partial x} \quad \frac{\eta}{\tau(\alpha\eta + 1)}(\alpha u - v) = 0$$

$$\frac{\partial v}{\partial t} - \frac{\partial v}{\partial x} - \frac{1}{\tau(\alpha\eta + 1)}(\alpha u - v) = 0$$

with boundary and initial value conditions:

$$u(0,t) = \frac{1}{1 + \lambda}(v(0,t) + \lambda w(t))$$

$$v(\frac{K}{K + 1} \cdot \overline{y}, \frac{1}{K + 1}\overline{y}) = v(\overline{y},0)$$

$$K = \eta(1 + \lambda)$$

u : isotope ratio of liquid phase
v : isotope ratio of solid phase
w : isotope ratio of liquid precipitation
x : depth of column in units of total height
t : time in units of total melting time
α : fractionation constant
τ : time constant
η : ratio of free water to solid phase in section of snow column
λ : ratio of volumes of liquid precipitation and original snow column

Isotope ratio of drain water from the column is given by $u(1 - t,t)$ $(t \geq 1/K + 1)$.

In the present experiment complete data on isotope ratios of original snow column, precipitation, and drain water is available for the first time. A computer program has been written to solve the equations. To use the program some simplifications of the real conditions must be made. Firstly, the first snow column must be divided into ten equal parts and the mean isotope ratio for each part calculated. The precipitation and drain water is treated in the same way. Secondly, the melting and precipitation is assumed continuous and constant.

The fractionation constant used for deuterium $\alpha_D = 1.0208$ has been measured [10]. $\alpha_T = 1.024$ for tritium has been found by using crude approximations and vapour pressure data [11].

With these assumptions and simplifications, isotope ratios for the liquid and solid phase of the snow column can be computed for different times and compared with experimental values. Moreover the isotope ratios of drain water are computed and can be compared with the obtained experimental values. Only measured isotope ratios of drain water are compared to the computed ratios. Adjusted as well as unadjusted data are listed in Tables 2 and 3 and the graphical comparison is shown in Figure 6.

Table 2

Deuterium

Adjusted data as prepared for the computer. For comparison
unadjusted data prepared in the same way are shown

		Column 1[1] -δ‰		Precipitation -δ‰		Drain water -δ‰	
		adj.	unadj.	adj.	unadj.	adj.	unadj.
Experiment 1970	1	76.6	75.9	75.8	75.9[2]	125.1	124.5
	2	76.6	75.9	75.8	75.9[2]	110.0	110.7
	3	116.8	106.1	75.1	75.9[2]	129.6	126.7
	4	139.7	138.9	74.8	75.9[2]	135.3	132.4
	5	144.5	142.9	74.8	75.9[2]	134.9	131.3
	6	145.0	144.8	75.0	75.9[2]	130.8	129.2
	7	140.3	139.5	75.5	75.9[2]	124.5	123.0
	8	144.0	142.0	75.5	75.9[2]	118.2	116.3
	9	166.7	165.8	75.6	75.9[2]	106.9	107.0
	10	133.3	133.2	76.7	75.9[2]	112.3	114.1
Water equiv cm		127.1	130.5	14.9	14.2	142.0	130.5
Experiment 1971	1	118.4	122.6	119.9	120.3[2]	142.0	140.8
	2	119.9	124.1	132.7	136.7	136.8	132.8
	3	126.2	130.5	128.0	120.5	131.2	128.3
	4	174.4	180.5	117.8	124.3	125.7	122.0
	5	146.1	151.3	114.3	109.4	121.1	113.9
	6	131.6	136.2	95.8	121.8	111.6	111.4
	7	129.1	133.6	84.5	98.4	111.6	111.4
	8	131.1	135.7	84.5	88.9	111.0	106.3
	9	109.4	113.2	84.5	77.3	102.2	101.5
	10	107.8	111.5	113.2	108.1	102.2	101.5
Water equiv cm		54.8	69.0	35.2	36.0	90.1	96.1

[1] Precipitation in period 1 was snow, which had melted, when column
2 was sampled. This precipitation in period 1 is added on top of
the column 1 before melting is assumed to start.

[2] Selected approximate values.

In Experiment 1970 the computed isotope ratios agree well with
the measured values with regard to simplifying assumptions involved:
Detailed information about the isotopic composition of precipitation
was lacking, the lysimeter was temporarily flooded by meltwater from
the outside. The free water content of snow could not be directly
measured and was assumed to be constant (10 or 20 per cent).

In Experiment 1971 large corrections of the water equivalent of
snow are involved affecting the details of diagrams in Figure 6.
However, the presence of isotopic exchanges in the melting snow
column is clearly shown and further confirmed by the comparison of
meltwater data with a hypothetical case without any exchange.

8. CONCLUSIONS

Results obtained for deuterium indicate the isotopic homogenization and enrichment of the snowpack in the course of melting. The recrystallization in the snowpack followed by an isotopic exchange between the liquid and solid phase appears to be the main cause.

Tritium results show that the top layers are the main source of snowmelt and that the meltwater penetrates the snowpack together with rain although with an appreciable exchange with lower layers.

The theoretical model of the isotopic fractionation was generally confirmed by the experimental results despite minor discrepancies. More detailed measurements are envisaged to prove the validity of the model as it is important for describing the firnification of temperate glaciers and processes taking place in the snowpack.

Table 3

Tritium

Adjusted data as prepared for the computer. For comparison
unadjusted data prepared in the same way are shown

	Column 1 T.U.		Precipitation T.U.		Drain water T.U.	
	adj.	unadj.	adj.	unadj.	adj.	unadj.
1	243	277	295	280[1]	118	130
2	138	157	321	326	129	135
3	111	126	326	322	157	153
4	91	104	372	344	210	210
5	76	87	410	414	210	215
6	48	54	288	414	156	217
7	35	40	214	260	156	217
8	67	77	214	212	158	193
9	50	57	214	212	183	170
10	49	56	311	298	183	170
Water equiv cm	54.8	69.0	35.2	36.0	90.1	96.1

[1] Selected approximate value

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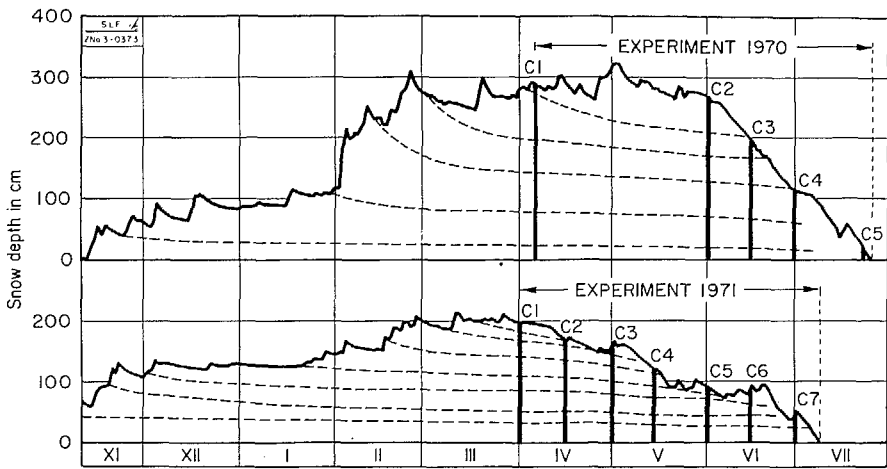
Fig. 1. Development of snow cover and sampling profiles,
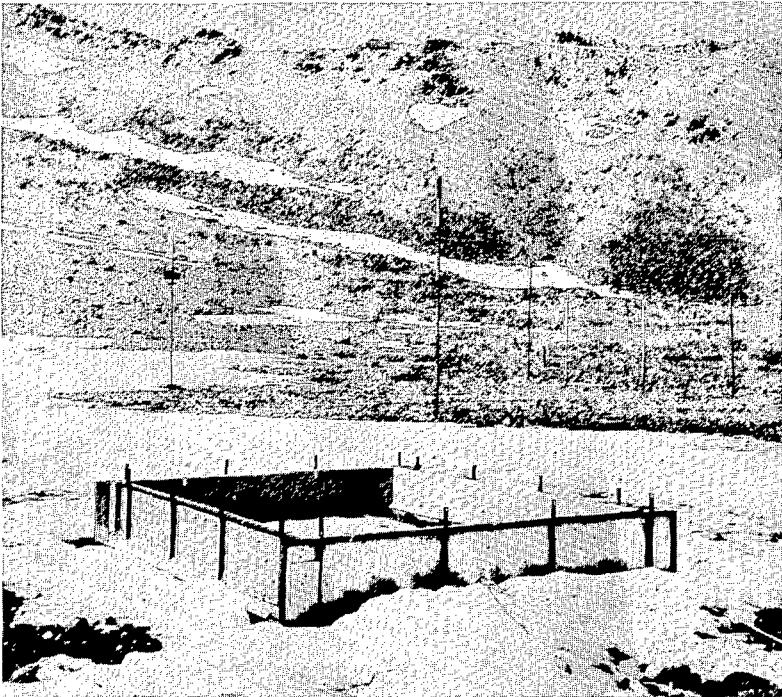Weissfluhjoch, 1969-70 and 1970-71

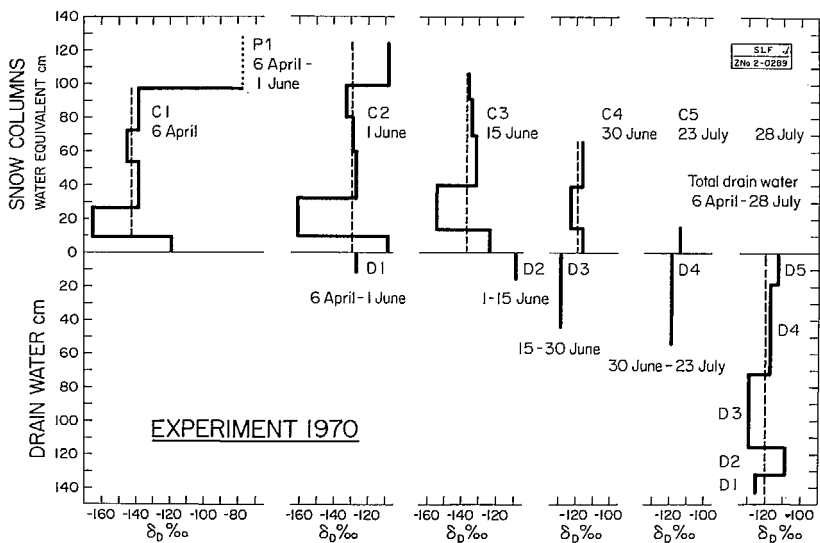Fig. 2.   Snow lysimeter at Weissfluhjoch, 2540 m asl

Fig. 3. Deuterium measurements, 1970. Broken vertical lines are weighted mean values of snow columns and total drain water
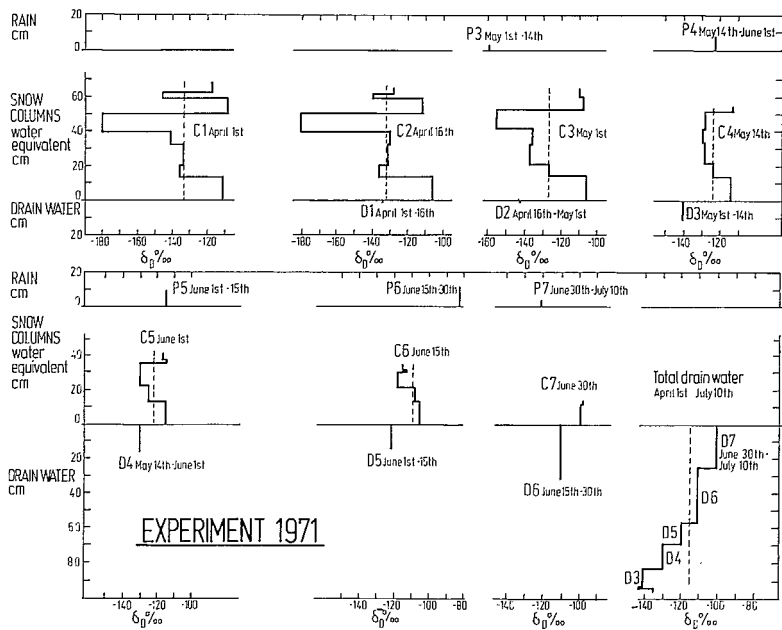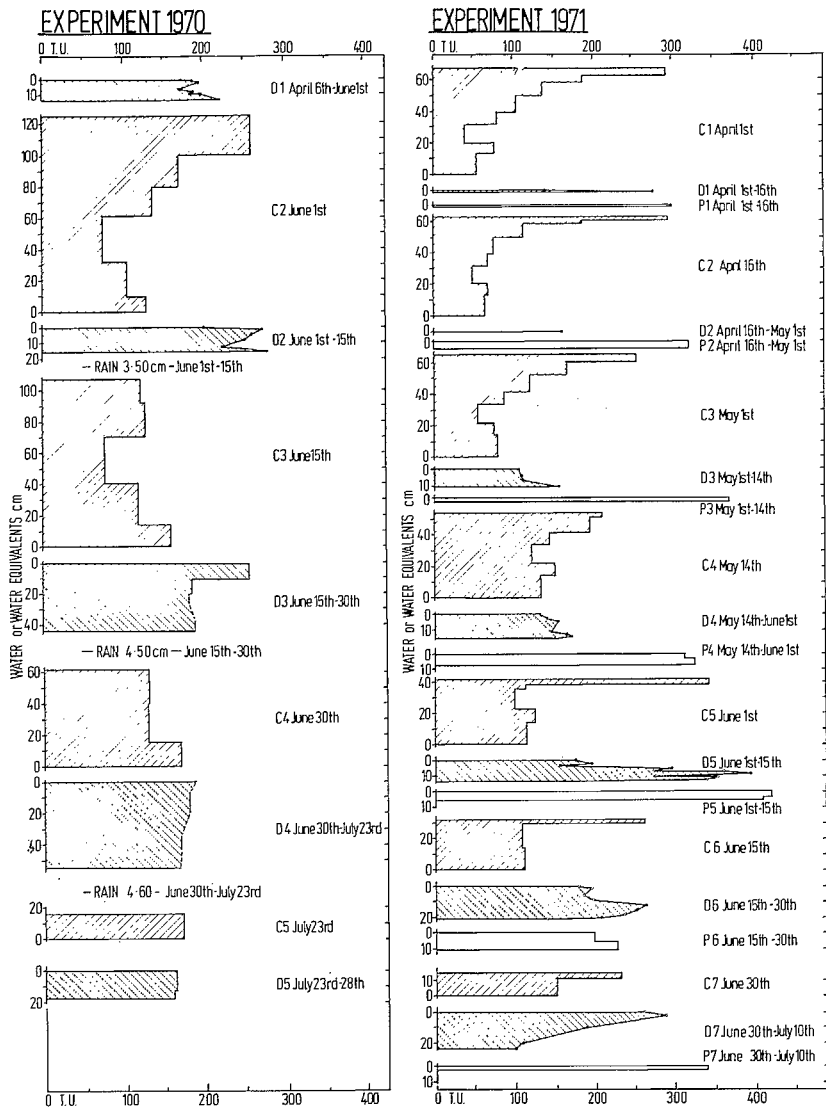

Fig. 4. Deuterium measurements, Experiment 1971
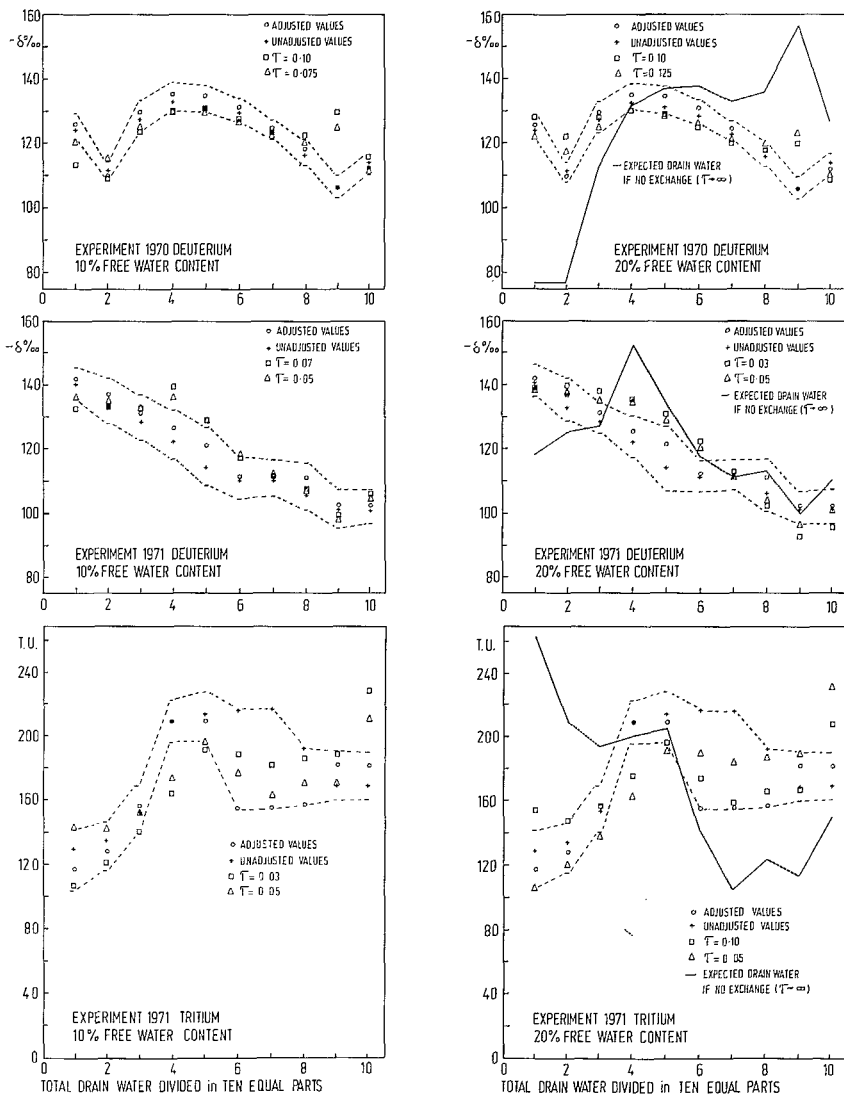
Fig. 5. Tritium measurements, Experiment 1970-1971

Fig. 6. Comparison of values calculated by the theoretical
model with direct measurements. Broken lines connect
the limits of double standard deviations

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DISCUSSION

K. West (Canada) - Have you done, or will you do, any O-18 analysis to study the equilibrium state of your samples?

J. Martinec (Switzerland) - We have considered deuterium data as rather equivalent to oxygen 18 data although it might not be true with respect to evaporation. But this was not the purpose of this study up until now. We might study this aspect but it depends always on facilities for the analysis of samples. The University of Iceland prefers deuterium but I have another project with the University of Pisa which prefers O-18. It might be really interesting to have data for both isotopes because there are fewer problems with stable isotopes than with tritium. In any case, we will use tritium as well.

F.A. Prantl (Canada) - I agree with Dr. Martinec that in his present study there is no need to use an additional tracer isotope such as O-18. Had the purpose been to check whether there is any deviation from the slope value of the linear relationship between δD and δO-18 given by Dansgaard and others, it could have been done with any two isotopes, D and O-18, or D and T, or T and O-18 under special conditions. For any of the two, linear relationships can be obtained. The slopes of the two curves will be different but these can be calculated from the fractionation factors of the isotope under consideration.