The altitude effect on the isotopic composition of precipitation and glacier ice in the Alps

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ABSTRACT

1. Simultaneously collected rain samples from 3 stations in the Alps (altitude difference 1680 m) show that the evaporation from falling drops causes an isotopic altitude effect of −0.2 ‰ per 100 m.
2. Despite the lack of altitude effect in Alpine snow fall, the summer melting and the wind erosion cause distinct isotopic variations in the net-accumulated material on Kesselwandferner.
3. These variations are reflected in the ice in the ablation zone, and they may be used for studying glacier flow patterns.

1. Introduction

The isotopic composition of precipitation depends on several parameters, such as the origin of the precipitating vapour, the degree of cooling since the beginning of the condensation, the evaporation of liquid precipitation during the fall from the cloud to the ground etc. Evaporation-condensation processes under equilibrium give precipitation with δ's[1] that are linearly correlated in a $\delta(D)-\delta(O^{18})$ diagram with a slope to 8, whereas fast evaporation from liquid precipitation makes the δ's change with slopes lower than 8. For further discussion of these problems reference is made to Dansgaard (1964) and Craig (1965). The preferential condensation of the heavy isotopic components causes successively decreasing δ's with decreasing condensation temperature. One consequence is a seasonal variation at high latitudes, and another one is an isotopic altitude effect with lower δ's in precipitation at higher altitudes, at least as far as orografic precipitation is concerned. An altitude effect of −0.6 ‰ per 100 m have been measured for $\delta(O^{18})$ in North Greenland (Epstein and Benson (1959). Dansgaard (1961) found −0.63 ‰ per 100 m for the Western slope of the Greenland Ice, whereas −0.9 ‰ per 100 m in Queen Maud Land, Antarctica, appears from a paper of Gonfiantini *et al.* (1962). In non-polar regions −0.2 ‰ per 100 m has been measured on the Norwegian West Coast (Dansgaard, 1961) and in a coastal area in Turkey (Payne, 1966). Evidently, the altitude effect varies from one region to the other, at least at high latitudes. At a given location in the mid Alps the average condensation temperature cannot be closely related to the elevation of the ground. A possible systematic altitude effect must, therefore, be ascribed to other parameters.

The Kesselwandferner has earlier been the object of a stable isotope study (Deutsch *et al.*, 1966). The seasonal variation of $\delta(O^{18})$ of precipitation was shown to be of the order of 14‰. In the firn the seasonal variation is reduced to 3 ‰ due to run off and refreezing meltwater.

The first attempt to study glacier flow patterns by stable isotopes was made by Sharp and Epstein (1958), who found only small variations in the Saskatchewan and Malaspina glaciers. The conditions for such studies are more favorable on polar glaciers (Dansgaard, 1961). Nevertheless, the aim of this paper is to study the

[1] The isotopic composition of water is given by the relative deviation of the isotope ratio from that of S.M.O.W. (Standard Mean Ocean Water, Craig 1961):

$$\delta = \frac{R_{\text{sample}} - R_{\text{SMOW}}}{R_{\text{SMOW}}} \cdot 10^3 \text{‰}$$

the R's being the O^{18}/O^{16} or the D/H ratios for the sample and the standard. The uncertainties of the δ values given in this paper are ± 1.5 ‰ for deuterium and ± 0.1 ‰ for O^{18}.

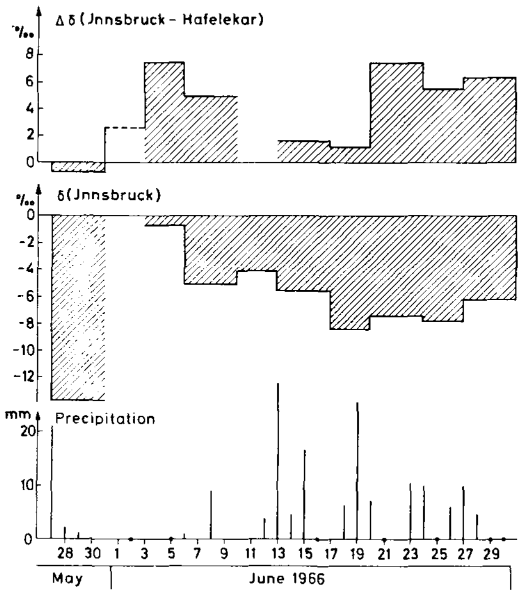

Fig. 1. Summer precipitation. Lower section: Amounts of precipitation at Innsbruck. Mid section: Mean $\delta(O^{18})$ of precipitation at Innsbruck. Upper section: Mean $\delta(O^{18})$ difference, $\Delta\delta$, between Innsbruck and Hafelekar.

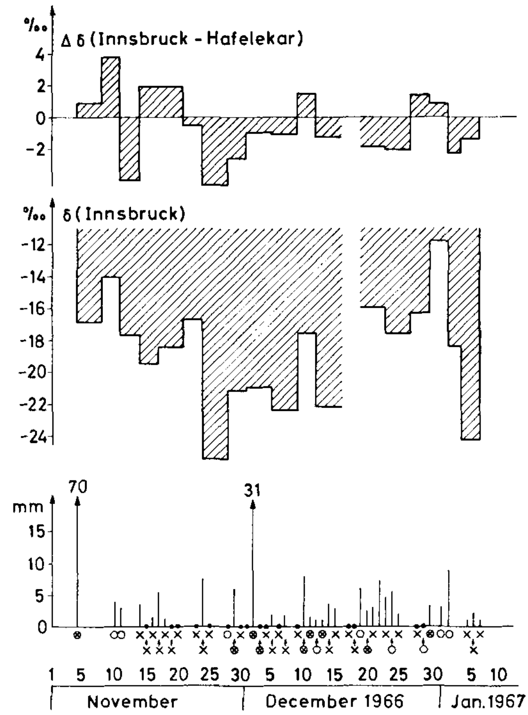

Fig. 2. Winter precipitation (cp. Fig. 1).

altitude effect on the isotopic composition of precipitation and on net-accumulated material on an Alpine glacier with a view to possible stable isotope studies of flow patterns.

In this paper the isotopic composition of the following series of samples will be discussed:

1. 10×3 precipitation samples from Innsbruck (station in the valley, 580 m altitude), Hungerburg (on the slope of the mountain, 860 m altitude) and Hafelekar (on the top, 2260 m altitude) collected from May 27th to June 30th 1966. The horizontal distance is 6 km between Hafelekar and the Innsbruck station and 3 km between Hafelekar and Hungerburg.

   The 3 precipitation collectors were emptiedsimultaneously twice a week. Significant evaporation from the collector is possible only in the periods June 6–10 and 13–17.
2. 20×3 precipitation samples from the same stations collected in the period from Nov. 4, 1966 to Jan. 7, 1967.
3. Samples from 6 pits in the accumulation zone representing the 1965/66 layer.
4. Samples from a 20 meter deep pit in the accumulation zone of the Kesselwandferner, representing the annual layers from 1951/52 to 1962/63.
5. Samples from a pit in the accumulation zone of Sonnblickkees (Hohe Tauern) representing the annual layers from 1960/61 to 1965/66.
6. 8 samples from a longitudinal section of the ablation zone of Kesselwandferner (Ötztaler Alps).

2. Results and discussion

2.1. *Isotopic altitude effect in recent precipitation* (series 1–2)

Fig. 1 shows considerable variations of δ for rain at Innsbruck as well as of its deviation, $\Delta\delta$, from δ for precipitation on Hafelekar. δ (Innsbruck) shows a slight, negative correlation with the amount of precpitation (amount effect, Dansgaard (1964)). The very low δ value of the first sample is close to the winter values (cp. Fig. 2), and the corresponding $\Delta\delta$ is the only negative one. These two facts indicate that the precipitation fell as snow till it reached low altitudes (the Hafelekar sample was collected from new snow. The mean temperature on May 27 was 7.4° at Innsbruck). However, $\Delta\delta$ is positive in the remaining 7 periods during which precipitation fell both at Innsbruck and on Hafelekar. The average $\Delta\delta$ is 5.0 ‰ corresponding to an altitude effect of -0.3 ‰ per 100 m for typical summer rain. The mean $\Delta\delta$ weighted with the amount of rain is 3.5 ‰ corresponding to an altitude effect of *-0.2 ‰ per 100 m*.

The reason for this altitude effect cannot be a difference in condensation temperature, because the condensation level is almost the same for precipitation falling at the two stations. It is more likely that the positive $\Delta\delta$ values are due to evaporation from the rain drops during their 1700 meter long fall between the Hafelekar and the Innsbruck levels, because the highest $\Delta\delta$ values occur in periods with small or moderate amounts of rain—in such periods the relative loss by evaporation and, thereby, the O^{18} enrichment of the drops will be highest under otherwise similar conditions.

Another indication of the evaporation being responsible for the altitude effect is the fact that winter precipitation shows no distinct altitude effect (cp. $\Delta\delta$ in Fig. 2). This is explained by the lack of fractionation by evaporation from ice crystals—the molecules are, roughly speaking, scraped off layer by layer, and the vapour pressure difference between the isotopic components has no effect.

Finally, the evaporation hypothesis is strongly supported by plotting $\delta(D)$ against $\delta(O^{18})$ for 3 of the summer rain triplets (Innsbruck–Hungerburg–Hafelekar) with highest $\Delta\delta$. Fig. 3 shows for the summer periods Nos. 4, 8 and 10 that the fall between the Hafelekar and Hungerburg levels causes the $\delta(D) - \delta(O^{18})$ point moving along a line with slope lower than 8, corresponding to fast evaporation, whereas during the rest of the fall (down to Innsbruck) the point moves with a slope close to 8 corresponding to evaporation under equilibrium conditions (due to high humidity at low altitudes).

The *conclusion* is that an isotopic altitude effect may occur by successive evaporation from falling wet precipitation released from essentially the same cloud level, whereas snow does not exhibit any distinct altitude effect under such conditions. The seasonal variation of $\delta(O^{18})$ is approx. 12 ‰ at Innsbruck and 9 ‰ on Hafelekar.

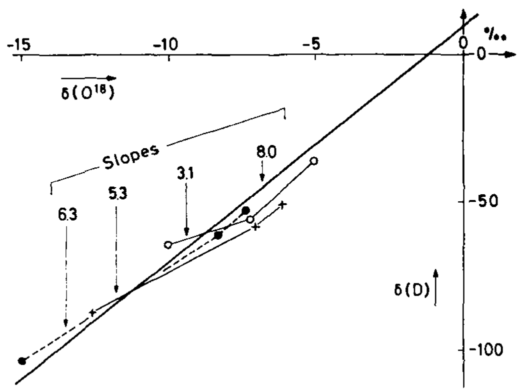

Fig. 3. $\delta(D)$ plottet against $\delta(O^{18})$ for three triplets of rain samples collected at altitudes of 580 m (highest δ's), 860 m and 2260 m (lowest δ's).

2.2. *Altitude effect in the accumulation zone of Kesselwandferner* (series 3)

The sites of collection (I–VI) are shown in *Fig. 4*. The individual $\delta(O^{18})$ values for the 6 samples of the 1965–66 layer are given in Table 1.

The high $\delta(O^{18})$ for sample No. I from the top of the glacier may be due to wind erosion of the winter snow with the lowest δ. The other samples indicate an altitude effect of the order of -2 ‰ per 100 m, i.e. much more than could be expected even in case of orographic precipitation. According to the above, no altitude effect at all should be present in snow accumulated on Kesselwandferner.

This may, in fact, also be true for the snow, when it falls on the glacier. It seems likely that the apparent altitude effect in the accumulated material is due to this material being exposed to varying degree of melting before the sampling took place. Thus, in the lower part of the accumulation zone the spring and winter snows with the lowest δ's have melted and run off, leaving only the precipitation from last fall with relatively high δ's, whereas in the mid part of the accumulation zone the remaining snow contains part of the isotopically light winter snow. Although mixing with seeping meltwater may blur the picure, the above interpretation seems basically correct.

The *conclusion* is that even though falling snow may have the same isotopic composition all over the glacier, the altitude dependent degree of melting, in connection with the sea-

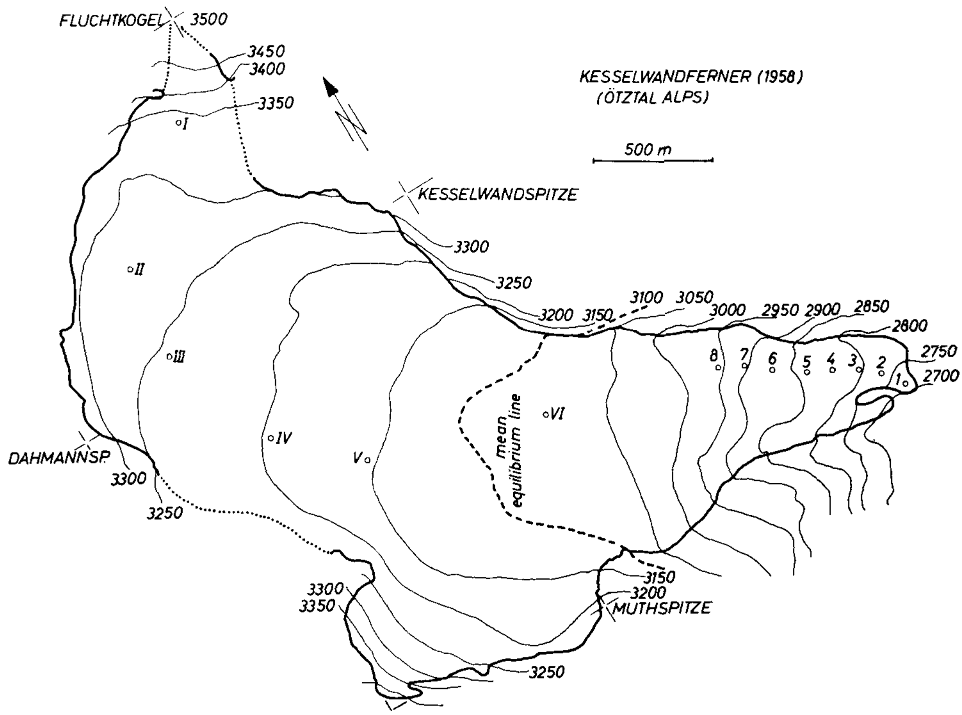

Fig. 4. Map of the Kesselwandferner. I–VI: locations of snow pits. 1–8: locations of ice sampling.

sonal isotope effect, causes a considerable isotopic altitude effect in the net-accumulated material. Seeping meltwater and wind erosion on the top of the glacier are disturbing factors.

2.3. *Isotopic variation of the annual layers* (series 4–5)

In Tables 2 and 3 are given the mean $\delta(O^{18})$ values of 11 and 4 annual layers of net-accumulated material at Kesselwandferner and Sonnblickkees, respectively.

The 20 m deep pit on Kesselwandferner shows a mean value of −14.4 ‰ i.e. 3 ‰ higher than that of the 1965/66 layer at the nearby location III (cp. Fig. 4 and Table 1), possibly because the 1965/66 layer was sampled before the end of the melt season.

δ-variations up to at least 6 ‰ must be ascribed to varying degree of melting from one year to the other, but also to varying isotopic composition of falling precipitation.

This latter fact appears from the last column of Table 3 showing the weighted mean $\delta(O^{18})$ of monthly samples (September–March) of precipitation collected in Vienna (Dansgaard, 1961–67). The 1962/63 value is 2.5 ‰ lower than the mean of the other four winter seasons.

The *conclusion* is that a representative sample for the net-accumulation at a given location on the glacier should involve several (4 or 6) years

Table 1. *$\delta(O^{18})$ of net-accumulated snow in 1965/66*

Pit No.	I	II	III	IV	V	VI
Altitude m	3340	3260	3240	3200	3150	3070
Thickness m	2.79	4.21	3.92	3.63	3.67	1.90
$\delta(O^{18})$ ‰	−15.35	−17.75	−17.35	−17.35	−14.80	−15.80

Table 2. *$\delta(O^{18})$ of net-accumulated snow close to pit III 1951–63*

Values in parenthesis refer to uncomplete sampling

Budget year	Thickness g/cm²	$\delta(O^{18})$ ‰	Budget year	Thickness g/cm²	$\delta(O^{18})$ ‰
1962/63	66	(−15.44)	1956/57	154	−14.85
1961/62	83	−10.90	1955/56	150	−14.08
1960/61	135	(−14.99)	1954/55	159	−13.40
1959/60	153	−16.44	1953/54	67	(−17.82)
1958/59	—	no sample	1952/53	85	−13.00
1957/58	83	−15.58	1951/52	39	−12.26

Weighted mean $\delta(O^{18})$: −12.88 ‰

Table 3. *$\delta(O^{18})$ of net-accumulated material at Sonnblickkees and weighted mean $\delta(O^{18})$ of Sept.–March precipitation in Vienna*

Sonnblickees			Vienna
Budget year	Thickness g/cm²	$\delta(O^{18})$ ‰	$\bar{\delta}(O^{18})$ ‰
1966/67			−12.2
1965/66	232	−14.93	−11.4
1964/95	238	−16.78	−12.6
1963/64	44	−12.90	−11.6
1962/63	—	no sample	−14.4
1961/62	96	−12.56	−12.0

Weighted mean $\delta(O^{18})$: −15.20 ‰

net-accumulation. Consequently, the data on the 1965/66 given in Table 1 cannot be used directly as references for a comparison between the isotopic composition of the ice in the ablation zone and that of material accumulated in the upper part of Kesselwandferner. The variation of the data in Table 1, however, may very well be typical.

2.4. *Isotopic variation in the ablation zone* (series 6)

The samples of ice from the ablation zone of Kesselwandferner were collected at the locations 1–8 shown in Fig. 4, and in such a way that their δ-values (Table 4) are considered representative.

The data in Table 4 show a minimum in the mid section of the ablation zone just like the data in Table 1 show a minimum in the mid section of the accumulation zone. The δ-variations are of the same order (approx. 2.6 ‰). This is in good agreement with the generally accepted flow pattern, according to which the ice formed close to the equilibrium line moves the short distance to the upper part of the ablation zone, whereas the ice formed on the top of the glacier moves close to the bottom all the way down to the terminus of the glacier tongue.

The *conclusion* is that the data indicate the possibility of using the stable isotopes for studying movement patterns in temperate glaciers. However, our accumulation data are not yet representative enough to allow further conclusions.

Acknowledgement

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Table 4. *$\delta(O^{18})$ of ice in the ablation zone of Kesselwandferner*

Site No.	1	2	3	4	5	6	7	8
$\delta(O^{18})$‰	−14.97	−15.60	−16.19	−16.00	−15.17	−13.63	−14.76	−14.28

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ВЫСОТНЫЙ ЭФФЕКТ В ИЗОТРОПНОМ СОСТАВЕ ОСАДКОВ И В ЛЕДНИКОВОМ ЛЬДЕ В АЛЬПАХ

1. Одновременно собранные пробы дождевой воды с трех станций в Альпах (разница высот 1680 м) показывают, что испарение с падающих капель вызывает изотопический высотный эффект в −0,2% на 100 м.

2. Несмотря на отсутствие высотного эффекта в альпийских снегопадах, летнее таяние и ветровая эрозия вызывают заметные изотопные вариации в аккумулируемом материале ледника Кессельвандфернер.

3. Эти вариации отражаются в составе льда в зоне абляции и могут быть использованы для изучения характера течения льдов.

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