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Discharge from active rock glaciers, Austrian Alps: a stable isotope approach

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Abstract

The discharge from two active rock glaciers in the Stubai and Ötztal Alps of Austria is characterized by strong seasonal and diurnal variations. The $\delta^{18}O$ and electric conductivity values of the melt water released at the rock glacier springs are lowest during high discharge at the beginning of the melt season. Both parameters progressively increase until late July to early August until the snow of the preceding winter is almost completely melted. This gradual increase in $\delta^{18}O$ and conductivity during the melt season is caused by a progressive decrease in the ratio of snowmelt versus icemelt plus groundwater. Melt water derived from summer rainfall events is quickly released from the rock glaciers within a few hours causing sharp peaks in discharge and less pronounced ones in $\delta^{18}O$, and a sharp decrease in conductivity. Isotopic and conductivity data therefore show that the water budget of these two ice-cored rock glaciers is mainly derived from snowmelt and rainfall, and to a lesser extent also from icemelt and groundwater.

Das Abflussverhalten zweier aktiver Blockgletscher in den Stubaier und Ötztaler Alpen (Österreich) ist gekennzeichnet durch starke saisonale und tägliche Schwankungen. Die $\delta^{18}O$ Werte und die elektrische Leitfähigkeit des Schmelzwassers, das an den Blockgletscherquellen entspringt, sind während hoher Abflüsse zu Beginn der Schmelzsaison am niedrigsten. Beide Werte steigen bis Ende Juni – Anfang August, bis der Schnee des vergangenen Winters weitgehend abgeschmolzen ist, kontinuierlich an. Diese graduelle Zunahme der $\delta^{18}O$ Werte und der elektrischen Leitfähigkeit während der Schmelzsaison wird durch eine kontinuierliche Abnahme des Verhältnisses von Schneeschmelze zu Eisschmelze plus Grundwasser verursacht. Schmelzwasser, das von sommerlichen Regenfall-Ereignissen stammt, wird von den Blockgletschern rasch innerhalb weniger Stunden abgegeben, was ein ausgeprägtes Maximum im Abfluss und etwas weniger stark ausgeprägt auch im $\delta^{18}O$ Wert, sowie eine deutliche Abnahme der elektrischen Leitfähigkeit, verursacht. Isotopendaten und elektrische Leitfähigkeitswerte zeigen an, dass das Wasser dieser beiden Eiskern-Blockgletscher zum Großteil von der Schneeschmelze und sommerlichen Regenfällen, und nur zu einem geringen Teil von Eisschmelze und Grundwasser stammt.

1. Introduction

Rock glaciers are debris-covered, slowly flowing mixtures of rock and ice common in many alpine and arctic regions (see Barsch, 1996; Haeberli, 1985; Whalley and Martin, 1992). They are striking morphological expressions of permafrost creep and belong to the most spectacular and most widespread periglacial phenomena on Earth (Haeberli, 1990). Rock glaciers are important agents of geomorphic landscape changes, particularly of alpine landscapes. They are widespread in mountain regions, but are less well studied than their (ice) glacier counterparts.

For many decades surprisingly little was known about the origin and evolution of rock glaciers resulting in long and controversial debates (e.g., Barsch, 1992, 1996; Clark et al., 1994, 1996, 1998; Haeberli, 1985, 1990; Haeberli and Beniston 1998; Haeberli and Vonder Mühll, 1996; Haeberli et al. 1999; Humlum, 1988, 1996; Potter et al., 1998; Vitek et al., 1987; Whalley and Martin, 1992; Whalley et al., 1994; Whalley and Palmer, 1998).

Wahrhaftig and Cox (1959), in a classical paper on rock glaciers, developed the idea that rock glaciers in the Alaska Range are composed of coarse rock debris connected by interstitial ice primarily derived from refrozen melt water. Several researchers have expanded this view, concluding that all rock glaciers are exclusively permafrost phenomena (Barsch, 1996; Haeberli, 1985). Shroder et al. (2000) based on studies on debris covered glaciers in the Nanga Parbat Himalaya proposed a mechanism by which glaciers can form into rock glaciers through inefficiency of sediment transfer from glacier ice to melt water.

In the Austrian Alps a large number of rock glaciers are present (Lieb, 1996), particularly in the Ötztal and Stubai Alps (Gerhold, 1967, 1969). Many of these rock glaciers are large and active covering a hitherto unknown area in this comparably strongly glaciated region of the Alps. Active rock glaciers are therefore not only among the most abundant and most striking morphological features of the periglacial environment in the Austrian Alps, but they also contain significant amounts of ice, which is protected from ablation by up to several metres of debris. Alpine glaciers have been studied since about 150 years and their response on climatic changes is fairly well understood (e.g., Haeberli 1995; Green et al. 1999; Grove 1997; Maisch et al. 1999). In contrast, the effect of global warming on active rock glaciers received attention only during the last two decades (Barsch 1996; Haeberli 2000, 2005). While the kinematics and thermodynamics of rock glaciers have since been studied in great detail (Arenson et al., 2002; Hoelzle et al., 2001; Isaksen et al., 2000; Jansen and Hergarten, 2006; Kääb et al., 2003; Lambiel and Delaloye, 2004; Heaberli et al., 2006), only little information is currently available on the hydrological regimes of active rock glaciers (Evin and Assier, 1983; Gardner and Bajewsky, 1987; Harris et al., 1994; Johnson, 1978, 1981; Krainer and Mostler, 2002). It is still unknown, for instance, how much water is released by the melting of internal ice, and what the relation is between the melting of winter snow relative to direct precipitation of rain and snow on the rock glacier during the melt season. It is also unknown how global warming affects the melting processes within the frozen core of active rock glaciers and thus the discharge pattern.

The aim of the present paper is to provide new information on the hydrological system of two active rock glaciers in the Austrian Alps, the Reichenkar rock glacier in the western Stubai Alps and the Kaiserberg rock glacier in the western Ötztal Alps, supplemented by data form two other active rock glaciers in the western Ötztal Alps and the Schober Group. All studied rock glaciers are "ice-cored rock glaciers" which developed from debris-covered glaciers (Berger et al., 2004; Krainer ans Mostler, 2000, 2001a, b; Krainer et al., 2002; Hausmann et al., 2007). The source of melt water released from these active rock glaciers was examined using O isotopes in conjunction with data of the discharge, water temperature and electric conductivity during two melt seasons. The stable isotopes of O (and also H) are invaluable tracers both in hydrogeology and in the study of snow and ice whose systematics are well understood (see reviews by Clark and Fritz, 1997 and Darling et al., 2005).

2. Setting

The Reichenkar rock glacier is located in a small, northeast-facing cirque called Inneres Reichenkar in the western Stubai Alps. The rock glacier is tongue-shaped and ice-cored, 1400 m long and between 260 m (near the head) and 190 m (near the toe) wide (Fig. 1, 2, 3). The rock glacier covers an area of 0.27 km² and extends from 2750 m down to an altitude of

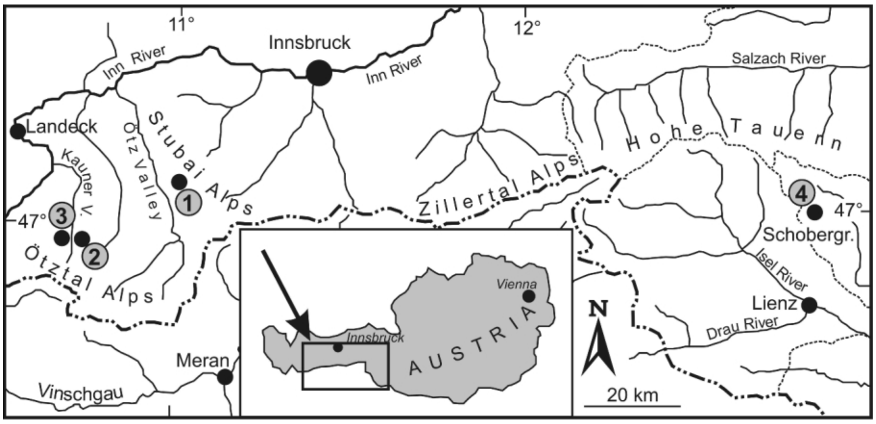

Figure 1: Location map of the studied rock glaciers: 1 Reichenkar, 2 Ölgrube, 3 Kaiserberg, 4 Langtal.

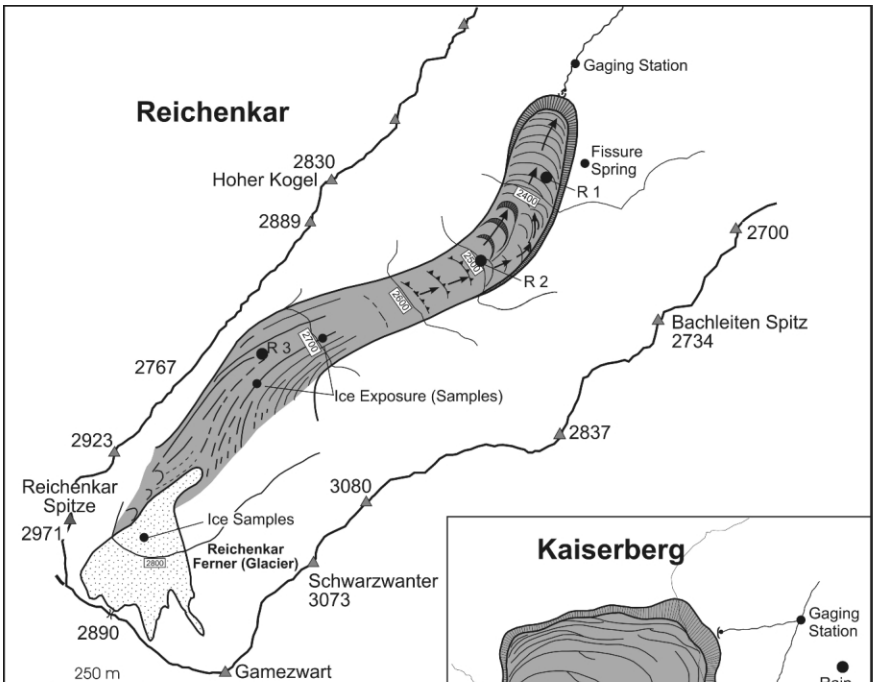

Figure 2: Simplified geomorphological map of the studied rock glaciers at Reichenkar and Kaiserberg. R 1, R 2 and R 3 indicate the locations of rainfall sampling sites on Reichenkar rock glacier.

Figure 3: View of the middle and lower portion of Reichenkar rock glacier.

2310 m. The frontal slope has a steep gradient (40 – 41°). The catchment area comprises 1.1 km² and the highest point of the catchment is at 3077 m (see Krainer and Mostler (2000, 2001 a, b, 2002) and Krainer et al. (2002) for additional information).

The Kaiserberg rock glacier formed in the upper reaches of the east-facing Kaiserberg Valley, a tributary of the Kauner Valley in the western Ötztal Alps (Fig. 1, 2, 4). This rock glacier shows a lobate form with a maximum width of 550 m and a length of 350 – 400 m. The frontal slope is active and steep (41-45°) and terminates at 2585 m, whereas the highest points reach 2710 m. The catchment area comprises 1.3 km² with the highest peak at 3112 m.

The Ölgrube rock glacier is located in the Innere Ölgrube, a small west-facing cirque of the Kauner Valley (Fig. 1). This composite rock glacier is 880 m long and 250 m wide and consists of two tongue-shaped lobes of varying activity sourced from two cirque walls separated by a ridge. The frontal slope is steep (40-45°) and active. The toe terminates at 2380 m, and the head extends to an altitude of 2750-2800 m. The catchment area comprises 2.1 km² with the highest peak at 3295 m (for further details see Berger et al., 2004).

The Langtal rock glacier is located in the upper part of Hinteres Langtal Kar, an east-facing small side cirque of the Gössnitz Valley in the northwestern part of the Schober Group (Hohe Tauern National Park; Fig. 1). The rock glacier extends from 2750 m down to 2480 m with a length of 600 m, covering an area of about 0.2 km². The catchment area measures 1.2 km² (Krainer and Mostler, 2001 b).

All four rock glaciers show a very coarse-grained surface layer containing blocks up to several meters in diameter. Most of the debris, however, is up to a few tens of centimetres in diameter and are composed of amphibolite, eclogite (Reichenkar), gneiss and micaschist (Ölgrube, Kaiserberg, Langtal). The surface topography is characterized by pronounced longitudinal and transversal ridges and furrows.

3. Methods

Gaging stations installed 20 to 100 m downstream from the rock glacier springs at Reichenkar, Kaiserberg, Ölgrube (one station each) and Langtal rock glaciers (two stations) continuously recorded the water depth of the melt water streams between late May and end of October. Discharge was determined using the salt dilution method (integration method). After measuring the discharge at different water depths, rating curves were established to calibrate water depth to discharge.

Electric conductivity (EC) was measured by using a handheld meter (WTW). At the gaging station of the Reichenkar rock glacier EC was logged at interval of 30 min between May 10, 2002 and September 10, 2002. Dye tracer tests using uranine were conducted in order to study the flow paths and residence time of the melt water on its way through the rock glaciers (for details see Krainer and Mostler, 2002).

For isotope analysis water samples were taken from the springs of Reichenkar and Kaiserberg rock glaciers during the melt seasons of 2001 and 2002 at a sampling interval of a few days. Melt water samples were also taken from Ölgrube and Langtal rock glaciers during 2001 at longer sampling intervals. At Reichenkar a spring discharging from a fracture in the biotite-plagioclase gneiss located about 20 m east of the snout of the rock glacier was also sampled for comparison. Although desirable, sampling at shorter intervals was impossible due to the difficult access of the sampling sites, We therefore consider this a preliminary study of seasonal trends in the isotopic composition of meltwater released from active rock glaciers.

Two snow profiles were dug and sampled near the front of the Reichenkar rock glacier in 2001 and 2002, and near the front of Kaiserberg rock glacier in 2002.

In 2001 three rain collectors were installed on the Reichenkar rock glacier at 2350 m, 2500 m and 2750 m and sampled at intervals of about 4 weeks. In 2002 samples were taken from the rain collector at 2350 m every 1-2 weeks. At the terminus of the Kaiserberg rock glacier a rain collector was installed in 2002.

Figure 4: View of the active rock glacier at Kaiserberg.

Samples were also obtained from ice exposed in the upper part of Reichenkar rock glacier in 2001 (10 samples) and 2002 (7 samples) at altitudes of 2700-2750 m, and from the Reichenkar glacier (3 samples). Deeply incised melt water channels exposed banded glacier ice below a 2 m thick debris layer at two localities, which was sampled for isotopic analysis.

The O isotopic composition was determined by equilibration with carbon dioxide using an on-line, continuous-flow system (Gasbench II) linked to a Finnigan Delta^{plus}XL mass spectrometer. Calibration of the mass spectrometer was accomplished using VSMOW, GISP, and SLAP standards. The 1-sigma analytical errors on the δ^{18}O values are ≤ 0.09‰.

4. Results

4.1. Discharge, temperature and EC

Water sourced from decaying internal ice, snowmelt and summer rain precipitation emerges at the foot of the front slope at all four rock glaciers (hydrology see Krainer and Mostler, 2002). The catchment area of Reichenkar rock glacier measures 1.1 km² (36% bedrock, 39% debris, 25% rock glacier). Annual precipitation and evaporation are estimated to be approximately 1400 mm and 250 mm (Baumgartner et al., 1983), respectively, resulting in an annual discharge of 36 L s^{-1} km^{-2}. Precipitation at the rock glacier from June 1 to August 29, 2002 was 471 mm and the discharge 66 L s^{-1} km^{-2}. The discharge per unit area for the same period, calculated from the gaging station, however, was 106 L s^{-1} km^{-2}. This discrepancy is explained by additional water derived from snow-and icemelt. The discharge per unit area for the melt period 2002 (mid May until mid October) calculated from the discharge measurements at the gaging station was 90 L s^{-1} km^{-2}.

The discharge of these springs is characterized by pronounced diurnal and seasonal variability. On July 2, 2001, for example, discharge at Reichenkar rock glacier increased continuously from 124 L s^{-1} at 12:00 to 190 L s^{-1} at 18:00, EC decreased from 34 to 29 µS/cm. Water temperature remained constant at 0.4°C. During the same time interval δ^{18}O remained nearly constant, ranging from -16.0‰ at 12:00 and -16.3‰ at 18:00.

Of interest are also the hydrological effects of individual

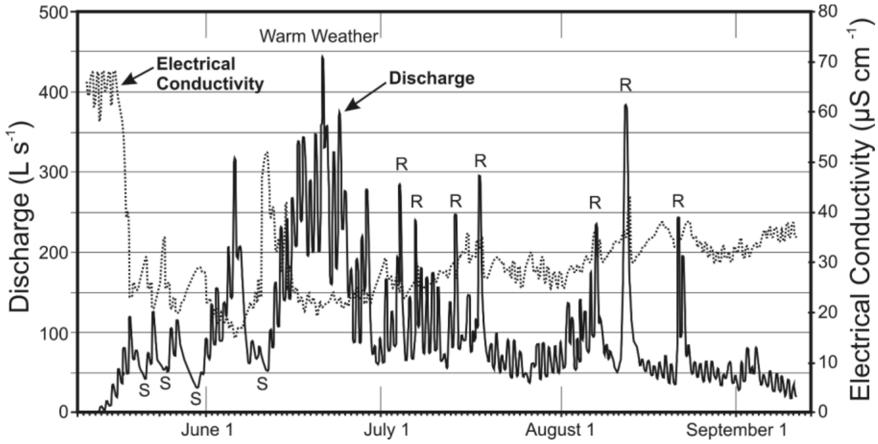

Figure 5: Hydrograph of the melt water stream at Reichenkar rock glacier (solid line) and electrical conductivity (stippled line) for the period from mid May to mid September 2002. Major snowfall events (S) with reduced discharge and rainfall events with peak discharge (R) are indicated.

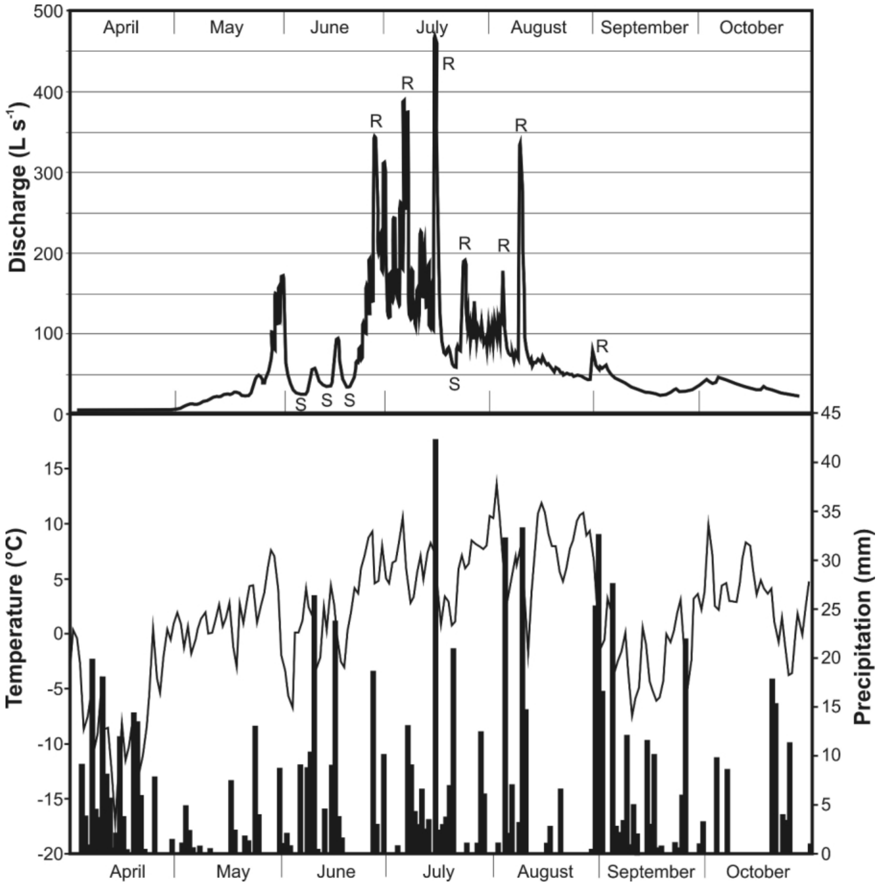

Figure 6: Hydrograph of the melt water stream emerging from the Kaiserberg rock glacier for the period April to October 2001. Snowfall events (S) and peakfloods caused by rainfall events (R) are highlighted.

rainfall events. Of the rainfall event on June 20/21, 2002 (26 mm precipitation) about 67% was released at the rock glacier spring within 48 hours. During this event baseflow was very high (200 L s^{-1}). In contrast, a rainfall event on June 27/28, 2002 resulted in 39 mm precipitation, but only 40% of the total precipitation was released within 48 hours after the event (baseflow only 70 l s^{-1}). The amount of precipitation per unit area for individual rainfall events during summer 2002 measured 400 – 600 L s^{-1} which was about 100 – 150 L s^{-1} higher than the peak discharge recorded at the gaging station immediately after these events.

Water temperatures of all studied springs remained below 1°C during the entire melt seasons. The EC values also show seasonal and diurnal variability, being lowest in spring and early summer due to the high amount of quickflow derived from precipitation and snow/icemelt and increasing towards autumn as a result of increasing baseflow. Two melt seasons from the Kaiserberg and the Reichenkar rock glaciers are described in more detail below (Figs. 5-7).

The 2001 melt season at the Kaiserberg rock glacier (Fig. 6) started on April 29 when discharge increased until a first peak of about 175 L s^{-1} on June 1. The following cold weather caused a significant decrease in discharge (minimum discharge of about 25 L s^{-1} on June 7). The discharge slightly increased afterwards and was interrupted again by drops in discharge between June 13 and 15 and June 20 and 21. After June 21 discharge strongly increased and discharge (150 - 470 L s^{-1}) peaked with low EC values (25-27 µS/cm) between June 28 and July 17, followed by a decrease until July 22. From late July onwards baseflow continuously decreased, interrupted by short peaks caused by rainfall events on August 5 and 10 and September 1. From September 1 until September 23 discharge continuously decreased to 25 L s^{-1} and and EC increased to 51 µS/cm, respectively. A period of warm weather in early October caused a slight increase in discharge until October 8 (70 L s^{-1}), followed by a continuous decrease to 10 L s^{-1} until November 11 (EC increased to 56 µS/cm).

The 2002 melt season at the Reichenkar rock glacier (Fig. 5) started at the end of April with low discharge and high EC values (59 – 68 µS/cm). Discharge increased significantly after May 16 resulting in a first peak (130 L s-1) on May 19. During this period EC decreased to 24 µS/cm. The lowest EC values (15 µS/cm) were recorded on June 6 as discharge increased to about 320 L s^{-1} due to a period of warm weather. Cooling caused a decrease in discharge to a minimum of about 50 L s^{-1} and an increase in EC (up to 52 µS/cm) on June 11. The following warm period resulted in very high discharge over a period of about 10 days with pronounced diurnal cycles. The highest discharge of the entire melt season 2002 was recorded on June 21 (about 450 L s^{-1}) with low EC values (21 µS/cm). Discharge only decreased during the second half of July, interrupted by individual discharge peaks caused by rainfall events. EC values increased continuously from 25 µS/cm during mid July to about 50 µS/cm at the end of September and 95 µS/cm at the end of November. A similar trend was recorded at Kaiserberg rock glacier with peak discharge of 600 L s^{-1} during the warm weather period in June (Fig. 7).

4.2 Stable isotopic composition

4.2.1 Reichenkar

Snow profile: Samples taken along a 120 cm thick snow profile at Reichenkar in 2001 showed significant variations in $\delta^{18}O$, ranging from -22.0‰ to -15.0‰ (Fig. 8). The highest value was measured at a boundary layer 25 cm above the base, the lowest value was recorded in a thin ice layer 95 cm above the base. Even within a homogenous snow layer between 25 and 58 cm the $\delta^{18}O$ values vary by about 6‰.

At the same location a 160 cm thick snow profile was also sampled in 2002. Overall, the $\delta^{18}O$ values of these samples were significantly higher than those of the preceding year (Fig. 10). The lowermost 60 cm thick homogenous snow layer showed only small variations in $\delta^{18}O$. The $\delta^{18}O$ values slightly increase to the top of the snow layer except for a thin snow layer immediately below an ice layer 75 cm above the base (-20.0‰).

Precipitation: Samples (aggregates of 4 weeks) of the three collectors show an increase in $\delta^{18}O$ from the end of May until the beginning of July (-9.5‰) of 2001 followed by a decrease

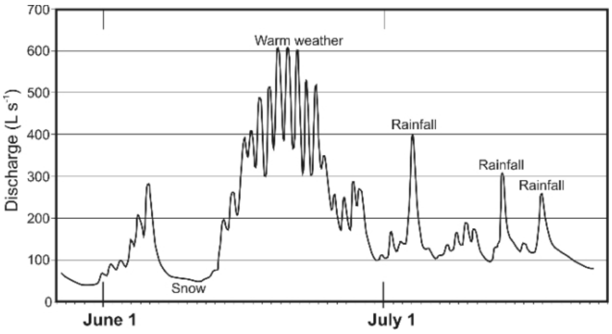

Figure 7: Hydrograph of the melt water stream at Kaiserberg rock glacier for the period May 27 to July 24, 2002. Peak discharge in June was caused by a period of dry and warm weather. The peaks in July were caused by rainfall events.

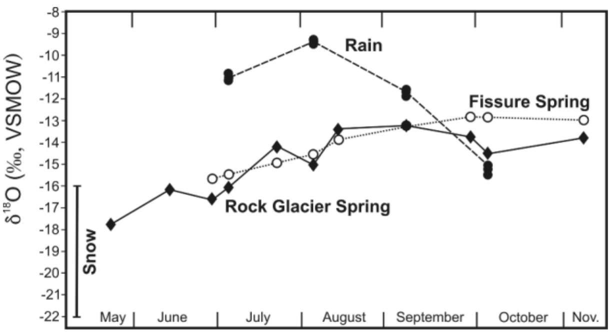

Figure 8: Oxygen isotope composition of the rock glacier spring, fissure spring, as well as of rain and snow at Reichenkar rock glacier during the period from June to November 2001. The snow profile was sampled in April.

to -15.5‰ at the beginning of October (Fig. 8). Although the rain collectors were located at different elevations with a total altitudinal difference of 400 m, there is no clear relationship between $\delta^{18}O$ and altitude. In 2002 only one rain collector was operating on the lower part of the rock glacier. Water in the collector was mostly derived from rainfall; a few snowfall events also provided some melt water. The overall trend is similar as in 2001: in early summer the values range between -10.5‰ and -10.0‰, increase to -9‰ and then decrease to -12‰ towards fall (Fig. 10). This trend corresponds well to that of the mean annual air temperature. Superimposed on this long-term trend are high-frequency variations in $\delta^{18}O$ indicating that the isotopic signature of individual precipitation events differed significantly (-15.6 to -7.2‰).

Rock glacier spring: The O isotopic composition of the rock glacier spring sampled over a period of about 6 months in 2001 ranges from -17.5‰ in early spring to -13.2‰ in late summer and fall (Fig. 8). The lowest $\delta^{18}O$ values occurred in late spring and the highest ones were recorded in late summer. The $\delta^{18}O$ values remained almost constant between late summer and fall.

Fissure spring: Water samples taken from the fissure spring, located at a distance of about 150 m from the rock glacier spring show the same $\delta^{18}O$ trend as the latter, albeit with lower amplitude (Fig. 8, 10).

Ice of the rock and cirque glaciers: Samples from ice-exposures taken in 2002 and 2004 show similar $\delta^{18}O$ values (-16.7 to -12.2‰ and -16.6 to -12.5‰, respectively). Ice of the cirque glacier has a similar O isotopic composition (-15.6 to-14.0‰) as melt water sourced from the cirque glacier (mean value -15.0‰). The isotopic composition of the ice is also similar to that of the water released from the rock glacier and fissure springs, but tends to be higher than that of snow and significantly lower than that of summer and autumn precipitation (Fig. 11).

4.2.2 Kaiserberg

Snow profile: The O isotopic composition of a snow profile dug near the gaging station on April 29, 2002 ranged between -23.4‰ and -11.8‰ (Fig. 12). The mean value (-17.7‰) is significantly lower than the lowest $\delta^{18}O$ value of the rock glacier spring.

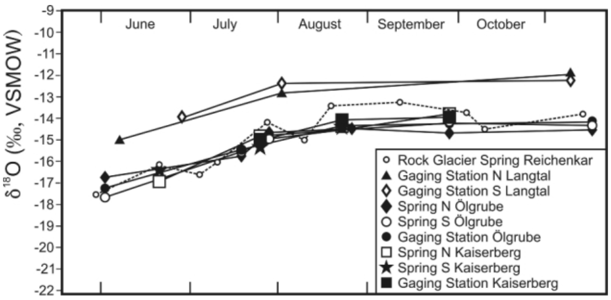

Figure 9: Oxygen isotope composition of melt water released from the rock glaciers at Reichenkar, Langtal, Ölgrube and Kaiserberg during 2001.

Precipitation: A high $\delta^{18}O$ value of -6.8‰ was measured at the rain collector at the beginning of the melt season on June 20, which was mostly derived from a precipitation event on June 16/17. The $\delta^{18}O$ values subsequently decreased and reached the lowest value of -16.3‰ on October 10 (Fig. 12).

Rock glacier spring: Samples taken from the northern and southern rock glacier spring show an increase in $\delta^{18}O$ from -17.0‰ in June to -13.9‰ in September 2001. In 2002 samples were taken every 1-2 weeks between April 29 and October 10. The lowest $\delta^{18}O$ values were measured in mid June during high discharge (-15.9‰). After mid June the $\delta^{18}O$ values continuously increased until mid August (-14.1‰) and then remained nearly constant until October, when discharge decreased again (Fig. 12).

4.2.3 Ölgrube

Water samples from two springs and the gaging station show the same $\delta^{18}O$ trend as at Reichenkar and Kaiserberg, characterized by an increase from the lowest values in May to the highest values in August, and relatively constant values from August until October (Fig. 9).

4.2.4 Hinteres Langtal Kar

The $\delta^{18}O$ values of the northern rock glacier spring increased from -15.0‰ at the beginning of the melt season (May 30) to -14.0‰ at the end of June, reached -12.3‰ at the end of July and finally -11.9‰ on November 2. A similar trend was observed at the southern rock glacier spring and the discharge of the lake (Hinterer Langtal See) located about 200 m downstream.

In general, $\delta^{18}O$ values recorded at Hinteres Langtal Kar are consistently higher (by about 2‰) than the $\delta^{18}O$ values measured at Reichenkar, Kaiserberg and Ölgrube (Fig. 9).

5. Discussion

5.1. Discharge patterns

Discharge measurements indicate that runoff from active rock glaciers depends on the climatic conditions, the thermal

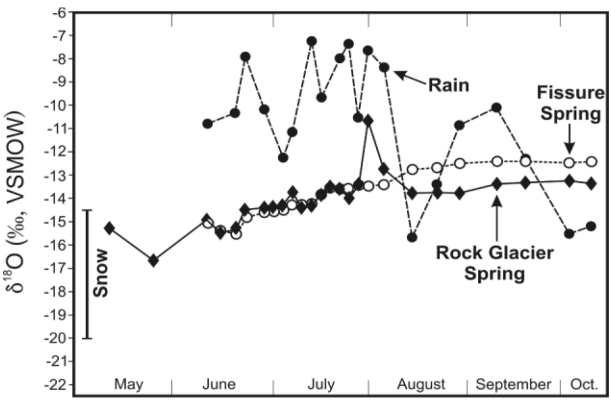

Figure 10: Oxygen isotope composition of the rock glacier spring, fissure spring, rain precipitation and snow at Reichenkar rock glacier during 2002. The snow profile was sampled in April.

conditions within the debris layer, and on the physical mechanisms controlling the flow of melt water through the rock glacier. Water released from active rock glaciers is derived from (a) snowmelt of winter snow, (b) melting of internal ice, and (c) atmospheric precipitation during the melt season, particularly by summer thunderstorms. Additionally a small amount of groundwater flows slowly through the sediment and fractured bedrock below the frozen core of the rock glacier. This groundwater, which is a mixture of snowmelt, rain precipitation and icemelt, is responsible for the high EC values during low discharge, but we assume that the groundwater has a negligible influence on the isotopic composition of the total discharge of the rock glacier.

Runoff rapidly increases in spring (May), particularly during warm weather periods. Peak discharge is recorded during June and July, mainly due to melting of winter snow and summer rainfall. This period of high discharge is interrupted by short periods of cool weather with snowfall in the mountains causing a pronounced decrease in discharge. During August, when the winter snow is almost completely molten, discharge significantly decreases, interrupted only by individual peak-flood events caused by rainfall. Fair weather periods cause intensive melting of winter snow producing pronounced diurnal runoff cycles with minimum discharge during noon and peak discharge late in the evening.

EC mirrors the discharge behavior of alpine rock glaciers. At the beginning of the melt season, as long as discharge is very low, EC is high, but rapidly decreases as discharge starts to rise. The lowest EC values are recorded during peak discharge in May, June and July. when also diurnal variations in EC are observed: minimum EC values occur during peak discharge late in the evening, and EC values reach their maxima during the lowest discharge at noon. In August, when almost all winter snow is gone, EC values continuously rise until the end of the melt season (interrupted by rainfall events).

5.2. Stable isotope trends

The δ^{18}O values of the rock glacier springs show a seasonal trend similar to EC. Melt water released at the beginning of the melt season is characterized by relatively high isotope values and high EC values. The increase in discharge during May coincides with a decrease in both δ^{18}O and EC, and during high discharge in May the lowest δ^{18}O and EC values are recorded. From May until August δ^{18}O and EC increase continuously. δ^{18}O values remain almost constant from August until the end of the melt season.

At Reichenkar, water released from the rock glacier spring and from the fissure spring, and ice of the rock glacier and cirque glacier shows similar isotopic compositions. On the other hand, these melt water δ^{18}O values are generally lower than the values of summer rainfall, but tend to be higher than those of samples taken from snow profiles.

The significantly higher δ^{18}O melt water values recorded at Langtal rock glacier (Schober Group) are caused by the different source areas of precipitation (e.g., Kaiser et al., 2002). At Schobergruppe a major component of the annual precipitation is derived from low pressure systems originating in the Mediterranean region. In contrast, most of the precipitation falling in the Ötztal Alps is derived from low pressure systems originating in the Atlantic Ocean or the North Sea. The difference in δ^{18}O of about 2‰ recorded by the rock glacier spring at Reichenkar during the snowmelt season between 2001 and 2002 may also be caused by a higher proportion of precipitation derived from the Mediterranean Sea in 2001.

The temporal evolution of δ^{18}O of the melt water in conjunction with discharge and EC data helps to constrain the origin of water released at the snout of rock glaciers. Intermediate δ^{18}O values at the start of the melt season when discharge is still very low (in the order of a few l/s only) reflect melt water with high δ^{18}O which re-froze during the preceding autumn and mixed with melt water with low δ^{18}O values derived from snowmelt. The subsequent drop in δ^{18}O during the massive onset of discharge in spring shows that this water is predominantly derived from the melting of winter snow. As melting of the snowpack progresses δ^{18}O values gradually increase and maximum values are reached during late July and early August. After the last winter snow disappeared, δ^{18}O values remain almost constant until the end of the melt season.

This overall trend of rising δ^{18}O values during the melt season – which resembles that of runoff from alpine ice glaciers (e.g., Behrens et al., 1971; Ambach et al., 1976) - therefore primarily reflects the decreasing proportion of snowpack melt relative to water released by icemelt (which has higher δ^{18}O values – see above). Three additional processes may contribute to this trend. (a) During summer the surface of the snow on top of the rock glacier will change its isotopic composition due to evaporation (Árnason, 1981) giving rise to enrichment in ^{18}O.

(b) Rainfall events during summer and autumn result in infiltration of water with higher δ^{18}O values into the rock glacier. The difference between winter (snow) and summer (mostly rain) precipitation in the high Alps is typically of the order of

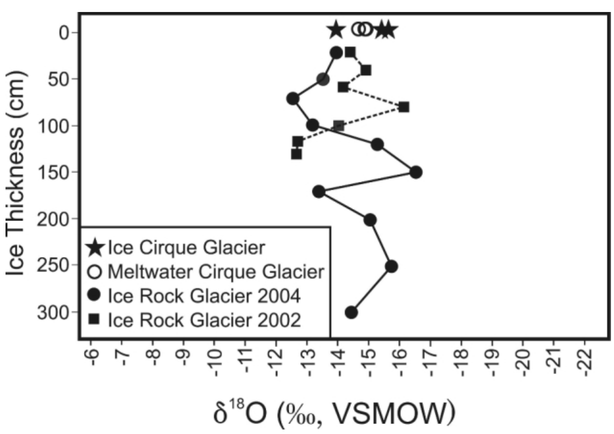

Figure 11: Oxygen isotope composition of ice from the rock glacier (sampled along two sections in 2002 and 2004) and of ice and melt water from the cirque glacier at Reichenkar. At both localities the ice was overlain by a 2 m thick debris layer.

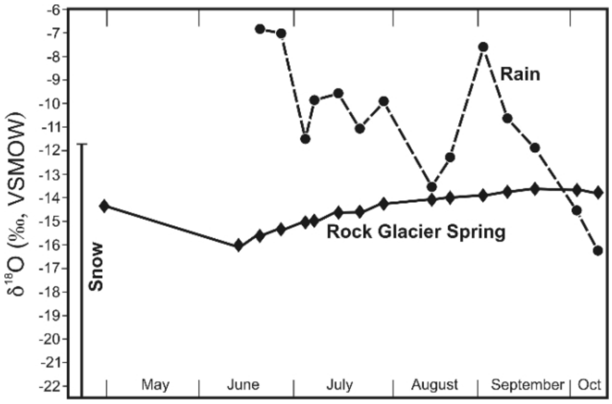

Figure 12: Oxygen isotope composition of the rock glacier spring, as well as of rain and snow at Kaiserberg rock glacier during 2002. The snow profile was sampled in April. The lowest value of the snow profile was -23.4‰.

ca. 14‰ (Deutsch et al., 1966), Although this isotopically distinct water may contribute to the overall rising $\delta^{18}O$ trend, its effect is regarded as small, because rainwater is rapidly transmitted through the rock glacier in a matter of a few hours resulting in short quickflow pulses (Krainer and Mostler, 2002).

(c) In a detailed isotopic study of snowpack melting in the Sierra Nevada Taylor et al. (2001) recognized that early in the season snowmelt shows low $\delta^{18}O$ values, which progressively increase as melting continues. This temporal trend of progressive enrichment in ^{18}O is explained by isotopic exchange reactions between water and ice. When snow melts at the surface, little isotopic fractionation occurs because the entire layer is melted. As this melt water percolates down, however, isotopic exchange takes place during which ice becomes enriched in ^{18}O relative to water dictated by the isotopic equilibrium between water and ice (e.g., Árnason, 1969). As a result of this, continuous melting of the snowpack gives rise to progressively higher $\delta^{18}O$ in the melt water. The same process also occurs in the Alps and elsewhere (Árnason, 1981) and may contribute to the general increase in $\delta^{18}O$ values as seen on all studied rock glaciers (Figs. 8 - 10). It is interesting to note, however, that isotopic studies of snow and firn on alpine glaciers reported that this alteration only affects individual snow layers, whereas intervening layers remained essentially unaltered during the ablation period despite melt water and rain infiltration (Ambach et al., 1972; Moser and Stichler, 1975, 1980).

This suggests that the melt water released at the rock glacier spring is a mixture of water derived from melting winter snowpack, which dominates the water budget during summer, and volumetrically smaller contributions from icemelt and rainfall. The temporally varying ratios of these water components give rise to the gradual increase in $\delta^{18}O$ and EC during the melt season. Unfortunately, however, the well documented increase in $\delta^{18}O$ during snowpack melting cannot be easily discriminated from the effect of decreasing mixing ratios of snowpack versus icemelt as the melting season progresses. Hence the contribution of icemelt to the overall hydrological budget of these rock glaciers currently remains the least well constrained component. Comparison of melt water compositions emerging from ice-cored rock glaciers and from ice-free (inactive) rock glaciers should allow to address this question. We also anticipate that ice-cemented rock glaciers, which differ significantly from ice-cored rock glaciers by a smaller amount of ice and different internal structures among other characteristic features, differ in their discharge behaviour and the stable isotopic composition of their runoff.

6. Conclusions

Melt water released from rock glacier springs is derived from snowmelt, icemelt, rain precipitation and groundwater. Snowmelt gives rise to melt water with relatively low $\delta^{18}O$ values, while summer rain shows much higher values. Water derived from icemelt has values similar to those of the rock glacier spring. The peak discharge during May and July is mainly caused by snowmelt. The $\delta^{18}O$ and EC values of the melt water released at the rock glacier spring are lowest during high discharge at the beginning of the melt season. The $\delta^{18}O$ progressively increase until late July to early August until almost all the winter snow is melted and then remain almost constant until the end of the melt season. This gradual increase in $\delta^{18}O$ and EC during the melt season is caused by a progressive decrease in the ratio of snowmelt versus icemelt plus groundwater. Our data, though sampled at coarse resolution, strongly suggest that water derived from summer rainfall events is transmitted through the rock glacier within a matter of hours resulting in sharp peaks in discharge and $\delta^{18}O$ peaks and concomitant drops in EC. For a more detailed characterization and quantitative hydrograph separation a shorter sampling interval and the possible use of additional water tracers will be necessary.

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