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# The Influence of Air Temperature on the Creep Behaviour of Three Rockglaciers in the Hohe Tauern

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## Abstract

The aim of this paper is to demonstrate the link between air temperature and the creep behaviour of three active rockglaciers. These are the Doesen, Hinteres Langtalkar and Weissenkar rockglacier, which are all located in the Hohe Tauern range, Eastern Alps, Austria. The surface motion of the investigated rockglaciers was measured using photogrammetric and geodetic methods. Exact annual displacement rates of at least the last ten years are the basis of this study. A comparison and analysis of the horizontal and vertical displacement rates revealed a rather homogenous and synchronous behaviour of the three rockglaciers despite their different size, morphology, complexity and mean annual velocity. The observed homogeneity led to the assumption that interannual variations are caused by external climatic factors. The horizontal displacement rates show a fairly clear correlation with variations in mean annual air temperature (MAAT) with a delay of about a year caused by their delayed propagation deeper into grounds. However, the vertical displacement rates seem to react quicker to the MAAT. Furthermore, the horizontal displacement rate of the Hinteres Langtalkar rockglacier is exemplary compared to the ice thickness change of the Goessnitzkees, a nearby small debris-covered cirque glacier. The objective is to show similarities between them, as this also indicates the dependency of flow velocities of rockglaciers on air temperature.

KEY WORDS: Hohe Tauern, rockglaciers, creep, horizontal and vertical displacement, interannual variations, MAAT

## 1. Introduction

Two issues arise from the title of this paper that need to be discussed in close connection, namely the creep behaviour of rockglaciers and the air temperature because rockglaciers are a climatically controlled phenomenon. How much climatic variations have a direct effect on the creep behaviour of rockglaciers was a question scientists could not agree on until a decade ago. Ever since an acceleration of the rockglacier movement has been detected (e.g. Schneider and Schneider 2001; Roer et al. 2005; Kääb et al. 2007; Kaufmann et al. 2007), a question that arises here is, if this is caused by the general, global warming, thus by an increased air temperature. This is where I put forth my working hypothesis. To what extent does the mean annual air temperature (MAAT) have an impact on the creep behaviour of rockglaciers, whereas the horizontal and vertical displacement rates will be examined in particular. This paper provides a thorough analysis and interpretation of the creep behaviour of three rockglaciers in the Hohe Tauern range, Austria in comparison to the MAAT. Some of the findings allow surprising interpretations. However, some questions remain unresolved. For this purpose an object of comparison, an ice glacier, is included into the discussion in order to find possible explanations and answers.

## 2. Study location and physiognomy of rockglaciers

The three observed active rockglaciers – Doesen, Hinteres Langtalkar and Weissenkar rockglacier – are all located in the Hohe Tauern range, Eastern Alps, Austria (cp. Figure 1). In this area under investigation the topographic, geologic and climatic conditions are favourable for the existence of permafrost at different altitudes and the frequent occurrence of rockglaciers (Lieb 1996).

The Doesen rockglacier (46°59' N, 13°17' O) is situated at the end of the glacially shaped, east-west trending inner Doesen valley in the Ankogel Group. The length of this tongue-shaped rockglacier is about 900 m and its width varies between 150 and 300 m. The total area of the rockglacier therefore amounts to 0.19 km$^2$. Its approx. 40° steep and maximum 45 m high frontal slope currently ends at ca. 2340 m above sea level (ASL), i.e. nearly 400 m under the present climatic snow line in the Hohe Tauern (ibid). The highest point of the rockglacier's rooting zone is at 2650 ASL.

The tongue-shaped rockglacier of the Hinteres Langtalkar (46°59' N, 12 °46' O), however, is located in the Schober group, the mountain range between Moell valley and Isel valley. It is a highly relief dependent and very active rockglacier which stretches from ca. 2455 m to 2700 m ASL. With an estimated length of ca. 750 m, a mean width of 100-250 m and an area of ca. 0.15 km$^2$ this landform is one of the biggest of its kind in the Schober Group (Lieb 1996; Krainer 2005). Striking is its very steep (> 40°) frontal slope that can be found beneath a terrain ridge. It has been assumed that the rockglacier advanced over this prominent terrain ridge in 1994 (Avian et al. 2005). Several transverse crevasses developed since (LIEB et al. 2004; Roer et. al. 2008). The current movement pattern distinguishes a faster lower part and a considerably slower upper as well as

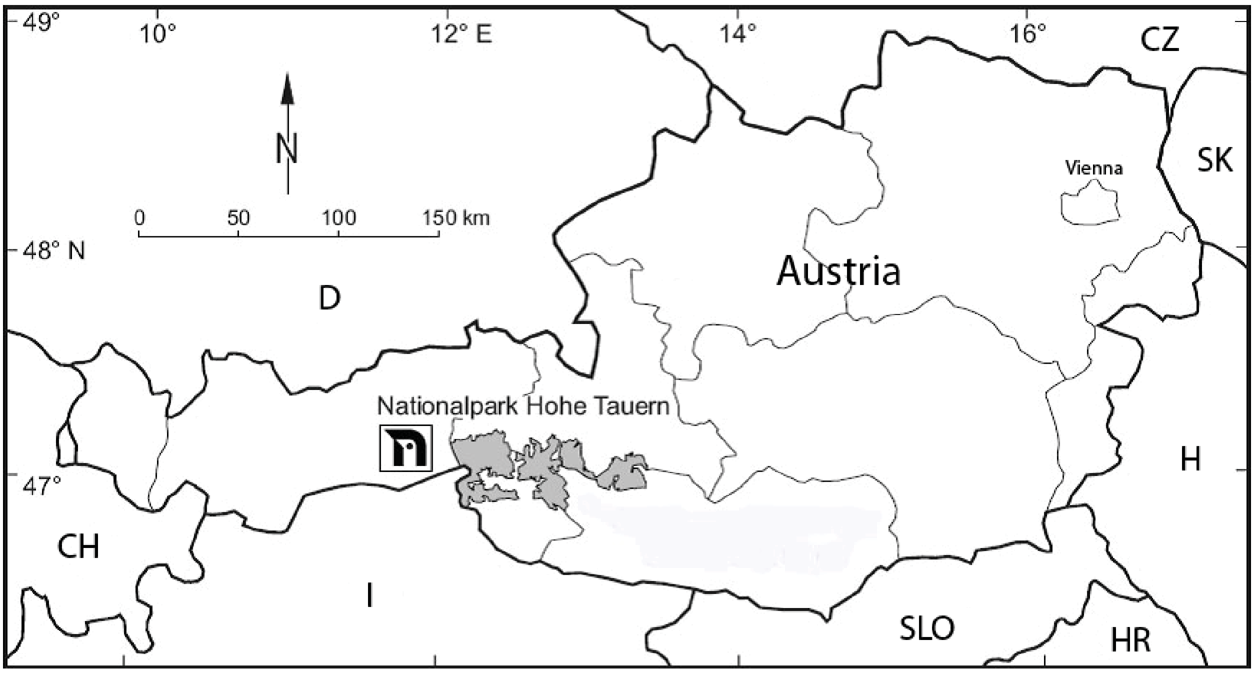


**Figure 1:** Location of the observed rockglaciers, Hohe Tauern national park, Austria.

orographic upper left part.

The Weissenkar rockglacier (46°57' N, 12°45' O) is situated in the same region as the latter one. This slowly moving tongue-shaped rockglacier is 500 m long, up to 300 wide and covers an area of 0,15 km². It ranges from 2610 m to 2720 m ASL. A feature of this landform is that it consists of an upper, active lobe which overrides a lower, inactive one (Kellerer-Pirklbauer et al., 2008). The lower part of the rockglacier is also characterised by well developed furrows and ridges.

## 3. Method

A lot of scientific work has been carried out on these three rockglaciers (Lieb 1996; Lieb et al. 2004; Avian et al. 2005; Kaufmann et al. 2006; Kaufmann et al. 2007; Kellerer-Pirklbauer et al. 2008). From these investigations the data and results of the following techniques have been used to interpret the creep behaviour of the rockglaciers.

Doesen rockglacier

- geodetic survey: precise data (horizontal and vertical displacement rates) from annual measurements of 34 object points since 1995; only in 2003 no remeasurements took place
- photogrammetric survey: several data from aerial photographs of the years 1954, 1969, 1975, 1983, 1993 and 1997

Hinteres Langtalkar rockglacier

- geodetic survey: exact data (horizontal and vertical displacement rates) from annual measurements of 38 object points since 1997; from the first measurement year 1997/98, only horizontal displacement rates exist
- photogrammetric survey: several data from aerial photographs of the years 1969, 1974, 1991 and 1997

Weissenkar rockglacier

- geodetic survey: precise data (horizontal and vertical displacement rates) from annual measurements of 18 object points since 1998; only in 2002 no remeasurements took place
- photogrammetric survey: data from aerial photographs of the years 1974, 1998 and 2002

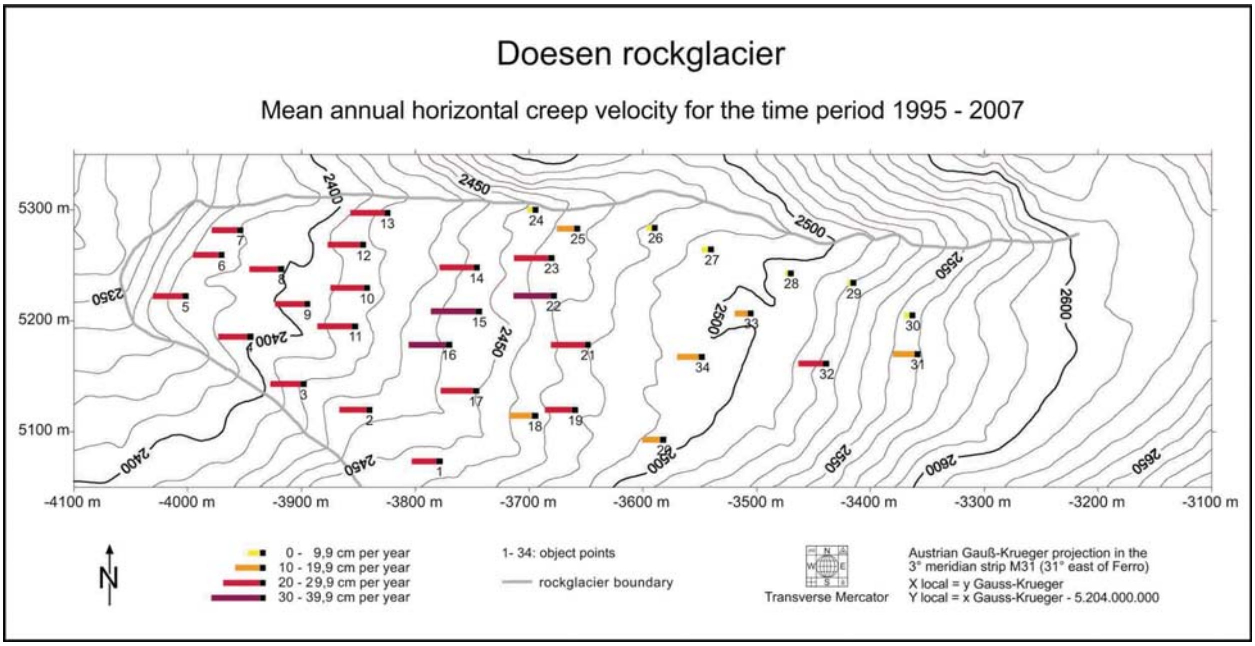


**Figure 2:** Doesen rockglacier – Mean annual horizontal creep velocity (1995 – 2007).

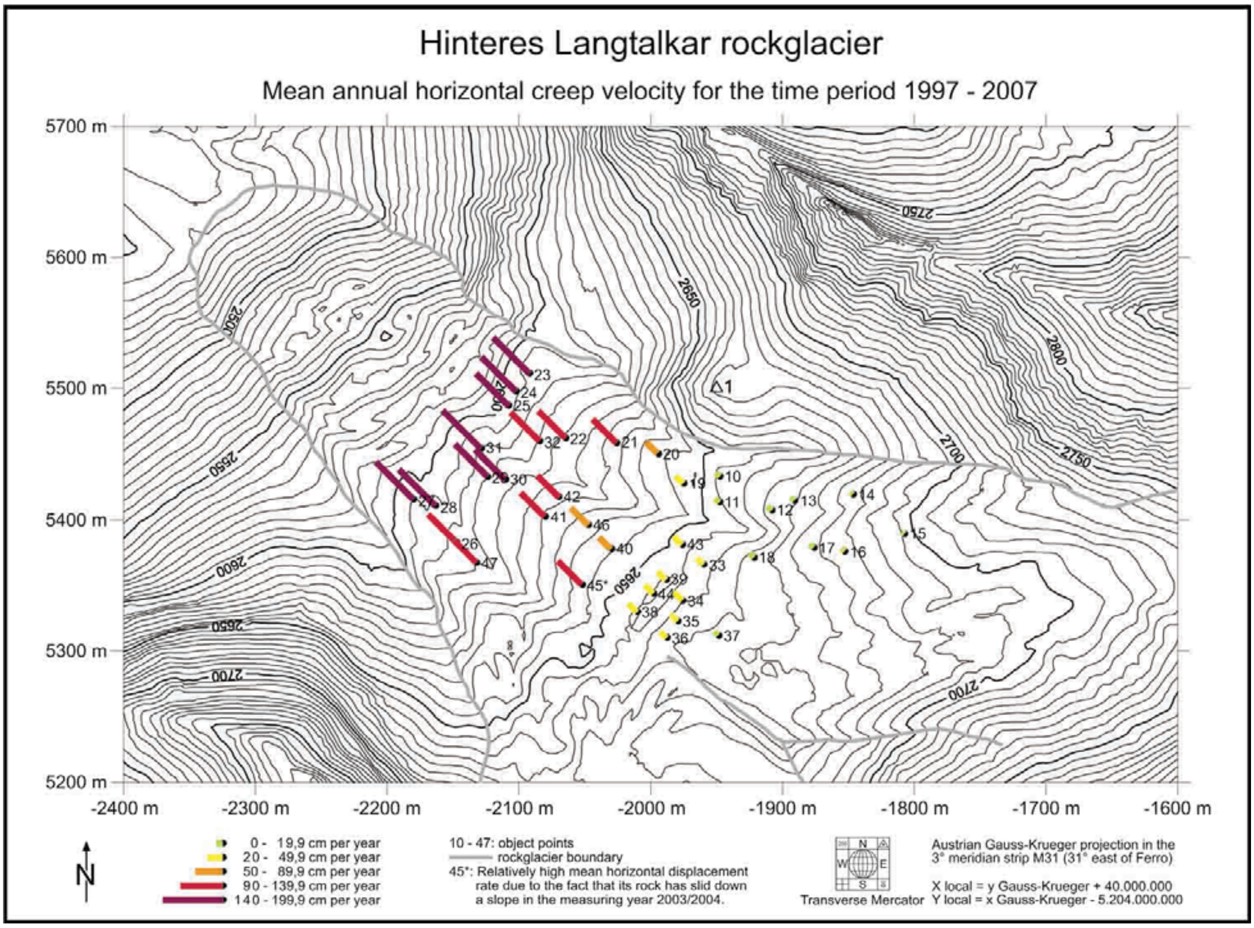


**Figure 3:** Hinteres Langtalkar rockglacier – Mean annual horizontal creep velocity (1995 – 2007).

## 4. Results and Discussion

The analysis of the horizontal and vertical displacement rates revealed a rather homogenous and synchronous behaviour of the three rockglaciers despite their different size, morphology, complexity and mean annual velocity. The highest horizontal velocities of all these landforms, for example, were measured around 2003. Other phases of higher creep rates are 2000/01, 2002/03 and 2004/05. In contrast, small horizontal displacement rates are quoted in 1999/2000, 2001/2002, 2005/2006 as well as 2006/2007. Similar tendencies can be observed for the vertical displacement rates. These findings indicate that the interannual variations in creep rates are caused by external factors. Since rockglaciers are a climatically controlled phenomenon and air temperature is the most obvious external factor, the creep velocity was then consequently compared with the mean annual air temperature (MAAT). To assure uniformity, the MAAT was taken from September till August of the following year because the annual measurements at each rockglacier are carried out in August or at the beginning of September at the latest. For all rockglaciers a certain correlation between the geodetic determined creep velocities and the corresponding MAAT of the preceding year was detected. This especially applies to those years in which the MAAT exhibited greater variations. The following discovery has been made: warm years entail greater and cold ones lower horizontal velocities. The delay of one year can be explained by a delayed propagation into deeper grounds. This finding confirms prior knowledge that permafrost reacts to climatic changes, e.g. variations of air temperature, with a time lag. It is a matter of common knowledge that rockglacier movement is only measured on its surface. However, rockglacier movement is mainly a consequence of the deformation of ice contained in them and of internal sliding on water films. Hausmann et al. (2007) were able to prove in a design model that higher ice temperatures amplify the internal deformation of a permafrost body. It therefore stands to reason to deduce that higher ice temperatures are mainly the result of higher air temperatures. Moreover, they also generate the development of water films. From the previously said one must then conclude: high air temperatures cause high creep velocities.

A question that arises from these investigations is, do

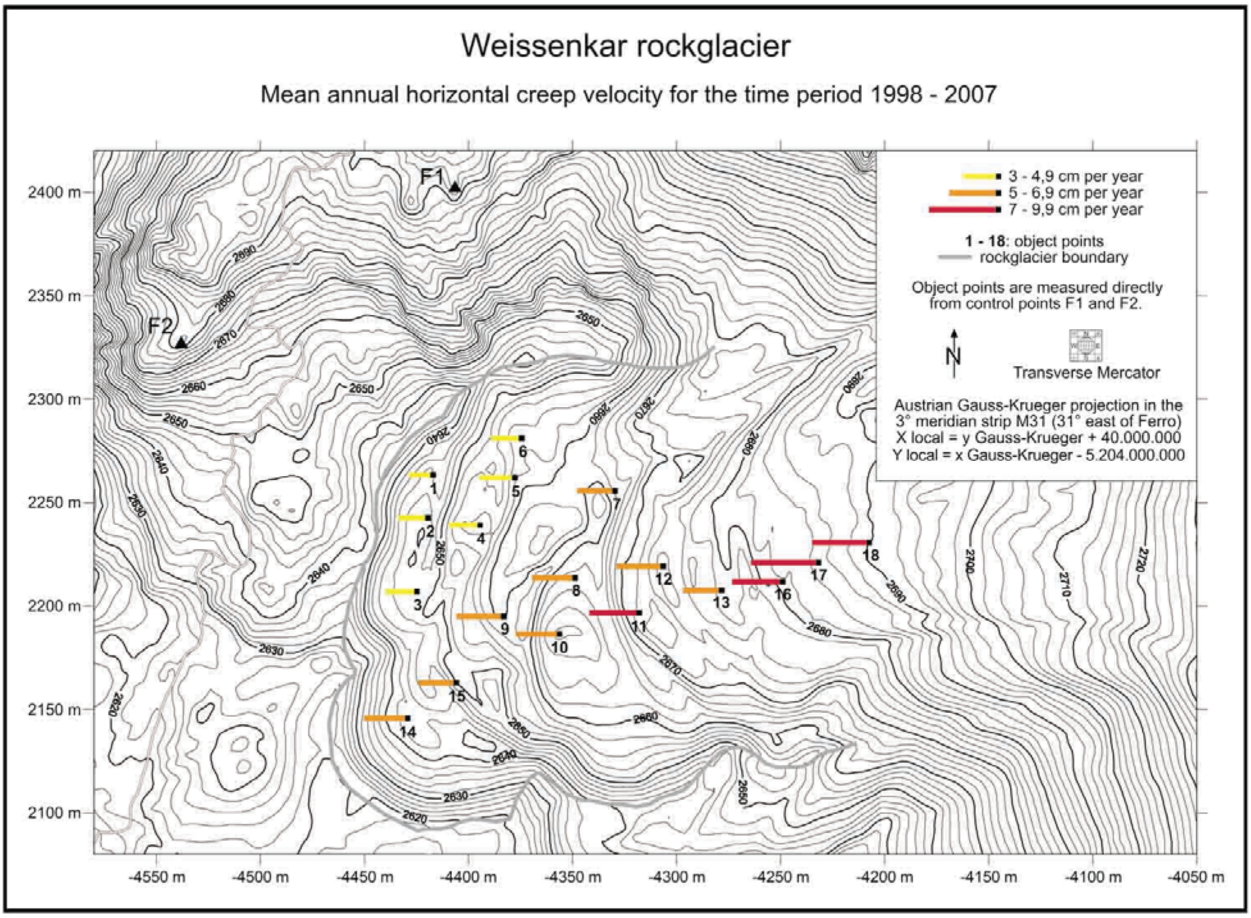


**Figure 4:** Weissenkar rockglacier – Mean annual horizontal creep velocity (1998 – 2007).

constant high air temperatures also cause constant high creep velocities. The time period from 1999/2000 till 2002/03, in which constant high temperatures were measured, can give information about this question. Contrary to the supposition the horizontal displacement rates do not show constant high values in the corresponding time period from 2000/01 till 2003/04 but steadily increasing creep velocities instead. Except for two groups of object points all other groups reach their highest ever measured horizontal displacement rates at the end of this period. An explanation for this could be that the constant warming of the ice body as well as the constant development of water films as a result of high air temperatures have increased the respective creep velocities so much that these accelerated even more. To be able to make such a statement, a longer time period needs to be examined. That way short-term fluctuations cannot invalidate the general statement (as it is the case for both groups of the Hinteres Langtalkar as well as the slower groups of the Doesen rockglacier), though it is still unclear what gives rise to these fluctuations.

The comparison of the horizontal and vertical displacement rates has brought about another important aspect. In general, the vertical creep rates decrease and increase slightly earlier than the corresponding horizontal ones. This phenomenon is best observable in those years in which the horizontal displacement rates increased considerably, i.e. in years that are preceded by a warm year or a hot period. This finding is observable in nearly all measuring years and groups. This leads to the supposition that the permafrost body had melted in the warmer periods. A melting ice body is mainly the consequence of higher air temperatures. Theoretically, the relatively high vertical displacement rates could also mean that the measured height loss of the object points in the corresponding years is the result of an extension of the ice body, which has the effect of thinning. The latter might even be the case in some years. Yet, this extension would then take place only in certain parts of a rockglacier and not all over the landform as it were then the case.

Another indirect proof for a melting ice body is the following explanations and calculations. There are object points that have on average a higher vertical than horizontal displacement rate during the term of geodetic measure-

**Doesen rockglacier**

mean annual horizontal displacement rate (cm/year)

| object points | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2001/2003 | 2003/2004 | 2002/2004 | 2004/2005 | 2005/2006 | 2006/2007 | mean value (1995-2007) | relative change (biggest value / smallest value) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| sum (24, 26, 27 and 30) | 8,7 | 9,5 | 14,8 | 21,1 | 12 | 31,3 | 11 | | | | 24,6 | 13,6 | 17,9 | 14,9 | 17,1 | 259,8% |
| mean value (24, 26, 27 and 30) | 2,2 | 2,4 | 3,7 | 5,3 | 3 | 7,8 | 2,8 | | | | 6,2 | 3,4 | 4,5 | 3,7 | 4,3 | |
| sum (20 and 31-34) | 58,2 | 63,5 | 83,5 | 74,3 | 68,5 | 99,9 | 65,5 | | | | 104 | 82,2 | 72,9 | 80,6 | 79,9 | 78,7% |
| mean value (20 and 31-34) | 11,6 | 12,7 | 16,7 | 14,9 | 13,7 | 20 | 13,1 | | | | 20,8 | 16,4 | 14,6 | 16,1 | 16 | |
| sum (1-27 and 30-34) | 504,5 | 515,9 | 658 | 663,7 | 554,7 | 721,5 | 693,5 | | | | 876,1 | 765,8 | 646,4 | 633,1 | 676 | 73,7% |
| mean value (1-27 and 30-34) | 15,8 | 16,1 | 20,6 | 20,7 | 17,3 | 22,5 | 21,7 | | | | 27,4 | 23,9 | 20,2 | 19,8 | 21,1 | |
| sum (10-17 and 21-23) | 241,9 | 248,4 | 300,1 | 310,2 | 260,1 | 325,1 | 329,5 | | | | 411,6 | 374,7 | 318,4 | 309,5 | 320 | 70,2% |
| mean value (10-17 and 21-23) | 22 | 22,6 | 27,3 | 28,2 | 23,6 | 29,6 | 30 | | | | 37,4 | 34,1 | 28,9 | 28,1 | 29,1 | |

**Hinteres Langtalkar rockglacier**

mean annual horizontal displacement rate (cm/year)

| object points | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2001/2003 | 2003/2004 | 2002/2004 | 2004/2005 | 2005/2006 | 2006/2007 | mean value (1997-2007) | relative change (biggest value / smallest value) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| sum (10-19, 33-39, 43 and 44) | | | 367,3 | 630 | 408,4 | 457,5 | 423,8 | 501,3 | | 539,1 | | 472,8 | 427,9 | 381,9 | 461 | 71,5% |
| mean value (10-19, 33-39, 43 and 44) | | | 19,3 | 33,2 | 21,5 | 24,1 | 22,3 | 26,4 | | 28,4 | | 24,9 | 22,5 | 20,1 | 24,3 | |
| sum (21-32, 41, 42 and 47) | | | 2257,2 | 2294,1 | 1897,5 | 2071,9 | 1889,2 | 2157,6 | | 2672,4 | | 2396,8 | 1897,5 | 1736,3 | 2127,1 | 53,9% |
| mean value (21-32, 41, 42 and 47) | | | 150,5 | 152,9 | 126,5 | 138,1 | 125,9 | 143,8 | | 178,2 | | 159,8 | 126,5 | 115,8 | 141,8 | |

**Weissenkar rockglacier**

mean annual horizontal displacement rate (cm/year)

| object points | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2001/2003 | 2003/2004 | 2002/2004 | 2004/2005 | 2005/2006 | 2006/2007 | mean value (1998-2007) | relative change (biggest value / smallest value) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| sum (1-6) | | | | 19,7 | 19,2 | 24,9 | | | 29,3 | 36,6 | | 23,8 | 19,8 | 20,6 | 24,8 | 90,6% |
| mean value (1-6) | | | | 3,3 | 3,2 | 4,2 | | | 4,9 | 6,1 | | 4 | 3,3 | 3,4 | 4,1 | |
| sum (7-18) | | | | 67,5 | 64,1 | 81,9 | | | 92,4 | 110,2 | | 70,5 | 59,8 | 69,6 | 78,9 | 84,3% |
| mean value (7-18) | | | | 5,6 | 5,3 | 6,8 | | | 7,7 | 9,2 | | 5,9 | 5 | 5,8 | 6,6 | |
| sum (11-13 and 16-18) | | | | 42,1 | 39,2 | 47,6 | | | 50,9 | 55,7 | | 33,5 | 36,2 | 37,1 | 43,7 | 66,3% |
| mean value (11-13 and 16-18) | | | | 7 | 6,5 | 7,9 | | | 8,5 | 9,3 | | 5,6 | 6 | 6,2 | 7,3 | |

**Doesen rockglacier**

mean annual vertical displacement rate (cm/year)

| object points | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2001/2003 | 2003/2004 | 2002/2004 | 2004/2005 | 2005/2006 | 2006/2007 | mean value (1995-2007) | relative change (smallest value / biggest value) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| sum (24, 26, 27 and 30) | -30,5 | -26,9 | -52,3 | -12,9 | -12,4 | -8,8 | -18,5 | | | | -25,2 | -11,7 | -7,8 | -12 | -20,2 | 570,5% |
| mean value (24, 26, 27 and 30) | -7,6 | -6,7 | -13,1 | -3,2 | -3,1 | -2,2 | -4,6 | | | | -6,3 | -2,9 | -2 | -3 | -5,1 | |
| sum (1-27 and 30-34) | -311,1 | -324,2 | -512,4 | -244,9 | -209 | -201,4 | -268,6 | | | | -320,4 | -246,6 | -175,1 | -219,5 | -279,1 | 192,6% |
| mean value (1-27 and 30-34) | -9,7 | -10,1 | -16 | -7,7 | -6,5 | -6,3 | -8,4 | | | | -10 | -7,7 | -5,5 | -6,9 | -8,7 | |
| sum (10-17 and 21-23) | -118,8 | -125,3 | -188,3 | -103 | -76,1 | -82 | -109 | | | | -128,1 | -115,9 | -78,9 | -85,1 | -111,2 | 147,4% |
| mean value (10-17 and 21-23) | -10,8 | -11,4 | -17,1 | -9,4 | -6,9 | -7,5 | -9,9 | | | | -11,6 | -10,5 | -7,2 | -7,7 | -10,1 | |
| sum (20 and 31-34) | -55,6 | -56,1 | -91,7 | -49,3 | -55,1 | -45,7 | -53,4 | | | | -67,1 | -41,1 | -40,1 | -57,3 | -56,7 | 128,7% |
| mean value (20 and 31-34) | -11,1 | -11,2 | -18,3 | -9,9 | -11 | -9,1 | -10,7 | | | | -13,4 | -8,2 | -8 | -11,4 | -11,3 | |

**Hinteres Langtalkar rockglacier**

mean annual vertical displacement rate (cm/year)

| object points | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2001/2003 | 2003/2004 | 2002/2004 | 2004/2005 | 2005/2006 | 2006/2007 | mean value (1997-2007) | relative change (smallest value / biggest value) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| sum (10-19, 33-39, 43 and 44) | | | | -127,2 | -244,3 | -277,2 | -276 | -416,1 | | -300,3 | | -256,7 | -299,3 | -317,9 | -279,4 | 227,1% |
| mean value (10-19, 33-39, 43 and 44) | | | | -6,7 | -12,9 | -14,6 | -14,5 | -21,9 | | -15,8 | | -13,5 | -15,8 | -16,7 | -14,7 | |
| sum (21-32, 41, 42 and 47) | | | | -846,3 | -721,7 | -811,6 | -756,5 | -902,4 | | -1111,3 | | -925,1 | -744,8 | -690,9 | -834,5 | 61% |
| mean value (21-32, 41, 42 and 47) | | | | -56,4 | -48,1 | -54,1 | -50,4 | -60,2 | | -74,1 | | -61,7 | -49,7 | -46,1 | -55,6 | |

**Weissenkar rockglacier**

mean annual vertical displacement rate (cm/year)

| object points | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2001/2003 | 2003/2004 | 2002/2004 | 2004/2005 | 2005/2006 | 2006/2007 | mean value (1998-2007) | relative change (smallest value / biggest value) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| sum (1-6) | | | | -6,5 | 4,3 | -2,9 | | | -5,05 | -8 | | 5,2 | -0,9 | -0,6 | -2,2 | 169,2% |
| mean value (1-6) | | | | -1,1 | 0,7 | -0,5 | | | -0,8 | -1,3 | | 0,9 | -0,2 | -0,1 | -0,4 | |
| sum (7-18) | | | | -46,6 | -32,9 | -33,5 | | | -60,5 | -55,9 | | -34,9 | -30,8 | -50,5 | -44,9 | 83,9% |
| mean value (7-18) | | | | -3,9 | -2,7 | -2,8 | | | -5 | -4,7 | | -2,9 | -2,6 | -4,2 | -3,7 | |
| sum (11-13 and 16-18) | | | | -35,8 | -31 | -26,1 | | | -46,85 | -39,9 | | -29 | -24,5 | -44,6 | -36 | 91,2% |
| mean value (11-13 and 16-18) | | | | -6 | -5,2 | -4,4 | | | -7,8 | -6,7 | | -4,8 | -4,1 | -7,4 | -6 | |

**Table 1:** Doesen, Hinteres Langtalkar and Weissenkar rockglacier – mean annual horizontal and vertical displacement rates of selected and grouped object points for the time period 1995 - 2007. Annotation: Due to the fact that the creep behaviour strongly varies within one rockglacier, the various object points are grouped so that comparability is given within one group.

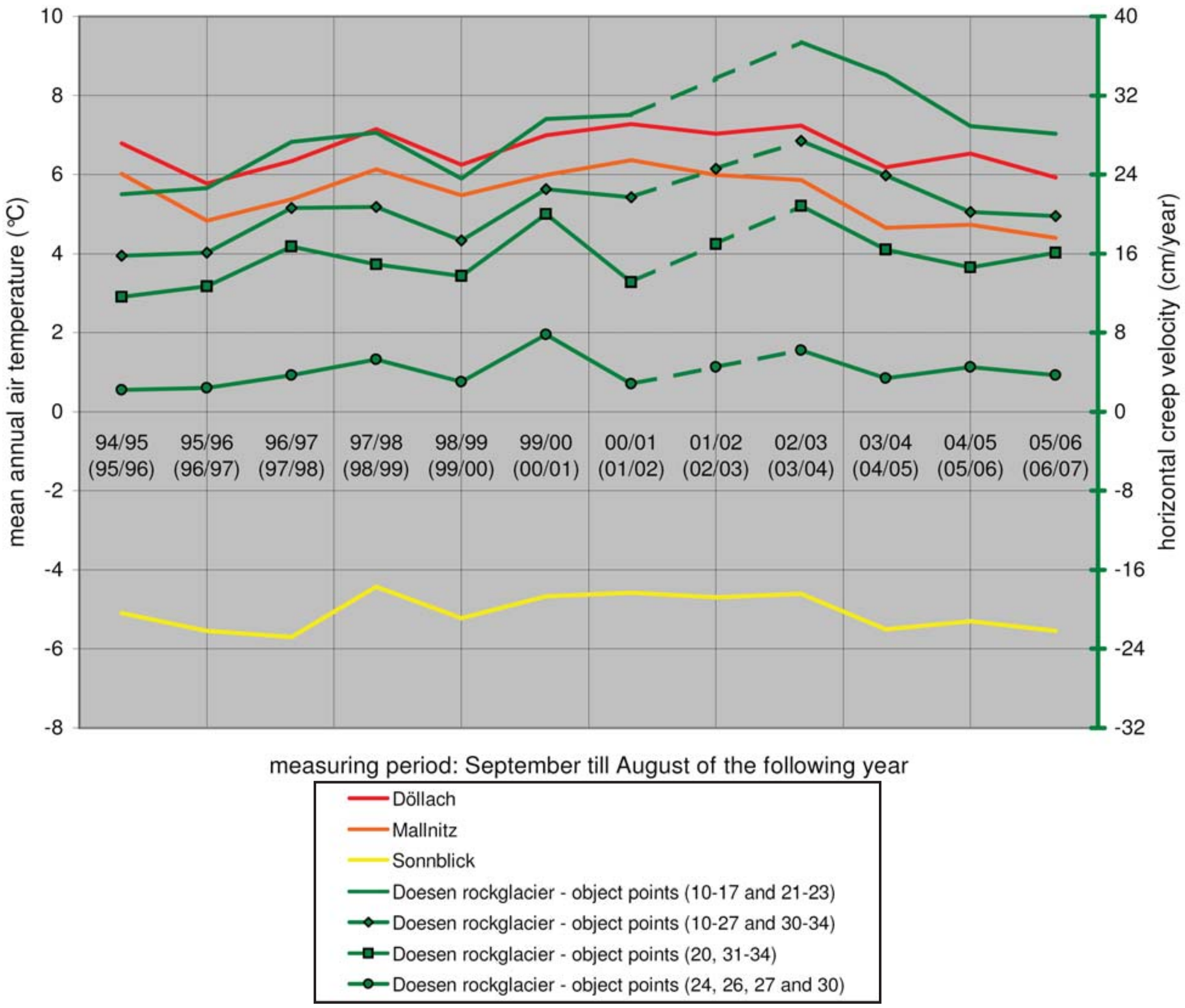


**Figure 5:** Comparison between the mean horizontal displacement rate of selected object points of the Doesen rockglacier and the mean annual air temperatures (MAAT) of nearby meteorological stations Annotation: measuring year without a bracket = measuring year of the MAAT; measuring year within a bracket = measuring year of the creep velocity; the dashed line indicates a two-year interval of measurement.

ments. One could argue that the particular rocks, on which these object points are installed, might have slid down a slope. A glance at the total displacement rates of these object points (e.g. Doesen rockglacier: object points 27 to 30) clarifies that a glide off can be excluded since the creep velocities are all to low. On the other hand, the relatively high vertical displacement rate could be the result of an extension of the ice body in a particular rockglacier part. The latter is, however, unlikely because almost all object points display a vertical displacement rate too high for the corresponding gradient. On the basis of these facts, only a melting induced, sunken permafrost body comes into consideration for the high vertical displacement rates. The following calculation should demonstrate this: First of all the average gradient of the rockglaciers needs to be calculated. This happens under the supposition that the landform has a smooth surface. The gradient is the difference in elevation between the highest and lowest point of the rockglacier divided by the length of the rockglacier. According to this, the average gradient of the three rockglaciers is approx. 34 % (Doesen rockglacier), 37 % (Hinteres Langtalkar rockglacier) and 20 % (Weissenkar rockglacier) respectively. Second step, all vertical as well as horizontal displacement rates must to be added. Afterwards the first sum must be divided by the second one. The result is the ratio between the horizontal and vertical displacement rates. The following ratios for the respective time periods are thus: -0.42 (Doesen rockglacier: 1995-2007), -0.44 (Hinterers Langtalkar rockglacier: 1998-2007) and -0.46 (Weissenkar rockglacier: 1998-2007). This means that for instance the object points of the Doesen rockglacier have dropped 0.42 cm in vertical direction per 1 cm in horizontal direction. Since the average gradient of the rockglacier was calculated with just 34 %, this means that the vertical elevation loss of the object points is on average 8 % more than the gradient actually allows for (Hinterers Langtalkar rockglacier: 7 % and Weissenkar rockglacier: even 16 %). These significant vertical elevation losses only allow the conclusion that the permafrost bodies of the three rockglaciers have melted in the mentioned period. To be able to definitely prove this hypothesis it would need a higher number of object points. It would be best if it had horizontal and vertical displacement rates of every single point of the rockglacier. However, since a multitude of object points are distributed evenly over the entire rockglacier a lot militates in favour of a melting ice body.

These explanations and calculations can, however, only give information on/about the fact that a melting of the permafrost body must have taken place but not how much the mass loss actually is. Estimations by Kaufmann (1998) and Lieb et al. (2004) support these findings. For further information on exact calculations see Kääb's continuous mass loss equation (cp. KÄÄB et al., 1998; KÄÄB, 2005).

Another important observation is that there are measuring years in which the already faster moving object points display a proportionally higher creep velocity than the slower ones and vice versa (The Weissenkar rockglacier is ignored here due to its specific creep behaviour as a result of the topographic characteristics and the very low mean annual flow velocity with minor differences). Years that represent the first case are 2002/2004, 2003/2004 and especially 2004/2005. What attracts the attention is that those years are at the end of a three-year time period with constantly high MAATs. It could be that the already mentioned consequences of a constant warming of the permafrost body (enhanced deformation of the permafrost body as well as an increased development of water films) mainly occur in the lower and middle parts of the rockglacier, where the faster object points are found. Two reasons for the comparatively high creep velocities in those parts could be a greater active layer as well as slightly higher ice temperatures which are the consequence of the

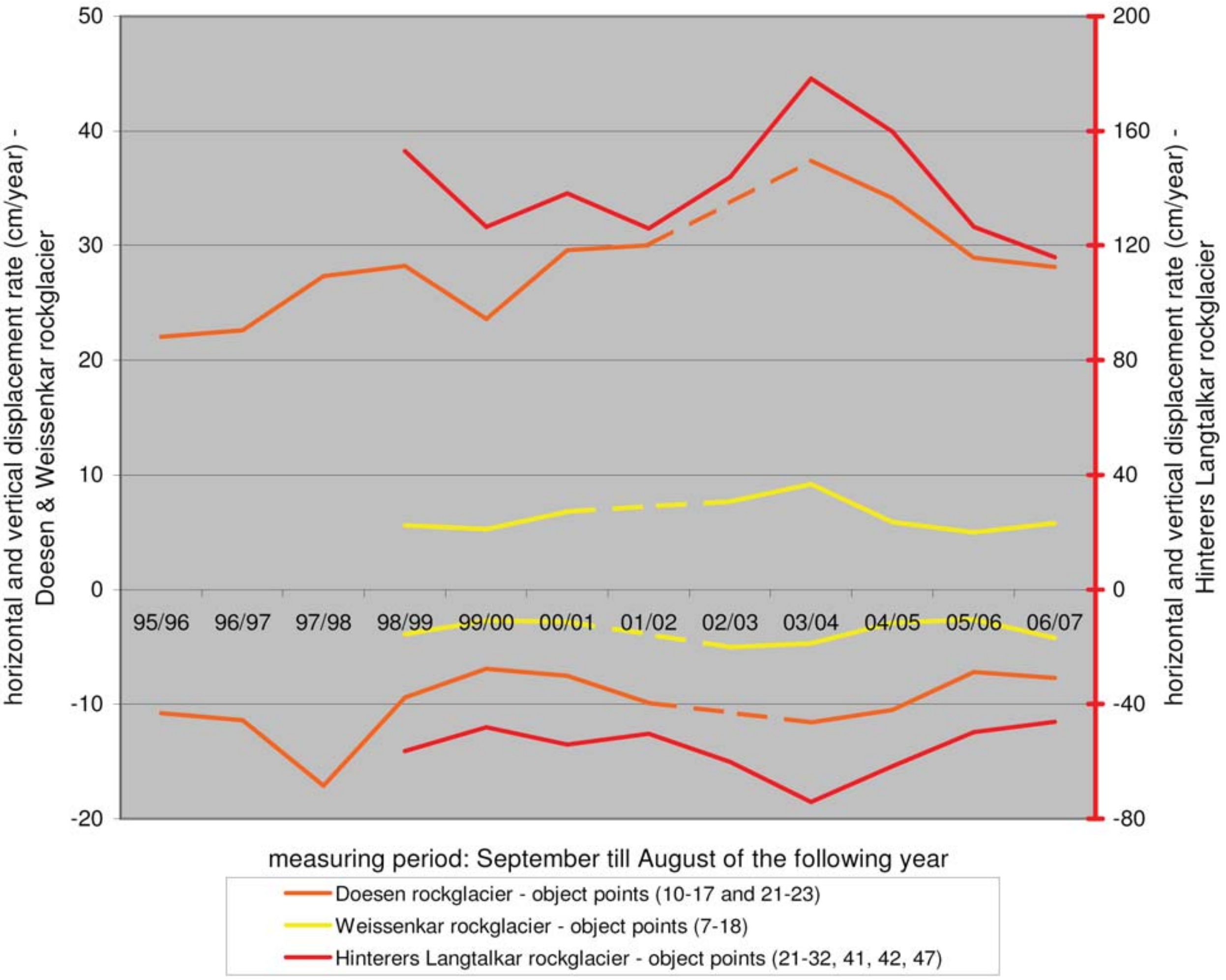


**Figure 6:** Comparison of the mean horizontal and vertical displacement rates of groups with a respectively higher average horizontal creep velocity of the three rockglaciers. Annotation: the dashed line indicates a two-year interval of measurement.

higher air temperatures at a lower height above sea level. Since the faster object points were proportionally fastest in 2004/05, one has to presume that the consequences of constant warming continue to have an effect on the lower parts. It therefore takes more than a year until the increased deformation comes to a halt. In other words, the faster a mass is put into motion the harder it gets to stop it. In the upper parts, where cooler temperatures are prevalent, the already weak internal deformation has quickly come to a halt by reason of the corresponding low MAAT of 2003/04.

The aforementioned thesis that the consequences of a constant warming mainly operate in the lower and middle parts is perhaps supported by the fact that the measuring years of 1998/99 and 2000/01, in which the slower moving object points are comparatively faster than the faster ones, are preceded by years in which the MAATs have just increased after a colder period. That means that in those years the effect/process of intensification has not yet been taken place. In other words, since the years before 1998/99 and 2000/01 were colder, the process of an intensified internal deformation, which is initiated through constant warming, could not be launched. Yet, the MAATs of those years are high enough to be able to assume that also the ice temperatures of the upper parts of the rockglaciers have risen markedly. That way a relative increase of the internal deformation could occur. Mathematically spoken, a small value can get bigger more easily than a big one.

Maybe this approach is also an explanation for the last aspect which refers to the relative change, namely that generally speaking the percentages of the relative change of groups with the highest mean horizontal creep velocity increase to those with the lowest one. The relative change is computed within one group between the sum with the lowest and highest horizontal/vertical displacement rate. If these values are, in a next step, compared with the relative change of other groups, e.g. the slowest and the fastest moving group, the aforesaid connection is being displayed (cp. Table 1). A reason for this could be that as soon as a rockglacier has really come into motion (result of a higher MAAT), those parts of a rockglacier that normally show little movement then feature a relatively higher internal deformation than those parts that already creep faster. A small value (small displacement rates) is proportionally becoming greater more quickly than a great one (high displacement rates).

## 5. Exemplary comparison of the ice thickness loss of the Goessnitzkees glacier with the mean annual horizontal displacement rate of selected object point of the Hinteres Langtalkar rockglacier

Despite all findings that have been gained through analysis and evaluation of the data of the three rockglaciers and the MAATs, some questions remain unresolved. In certain measuring years the creep behaviour does not show a correlation with the respective MAATs. To solve these unclarified points, an ice glacier, the Goessnitzkees, has been consulted as an object of comparison. The Gössnitzkees (46°58' N, 12°45' O) is a small debris-covered cirque glacier which is located in the immediate vicinity of the Hinteres Langtalkar rockglacier at the end of the Goessnitz valley. Since ice glaciers are much better explored than rockglaciers, the knowledge of these might help to answer the remaining open questions. First, the ice thickness loss of the Goessnitzkees will be exemplary compared with the creep velocity of the Hinteres Langtalkar rockglacier. Be it that a higher correlation is existent here than there is between the creep velocity and the MAAT of the preceding year, conclusions can afterwards be made about further factors which are responsible for the creep velocity of rockglaciers.

The comparison between the annual horizontal displacement rates of the Hinteres Langtalkar rockglacier and the mean annual ice thickness loss of the Goessnitzkees of the preceding year shows a high correlation (cp. Fig.7). This correlation is significantly higher than that of the horizontal velocities with the MAAT of the preceding year. Hence, the desired hypothesis has corroborated. With the exception of one year (2004/05 for the ice thickness change and 2005/06 for displacement rates respectively), both curves of the horizontal displacement rates run parallel to the curve of the ice thickness loss of the Gössnitzkees. Every time the creep velocity increases or decreases the, ice thickness loss becomes more or less.

Due to the high correlation between the mean ice thickness change of the Goessnitzkees and the horizontal displacement rates of the Hinteres Langtalkar rockglacier one has to assume that the creep velocity of a rockglacier is not just dependent on the MAAT but also on other factors as precipitation, mean annual ground surface temperature (MAGST) as well as on processes such as sublimation or ice and snow avalanches since these are jointly responsible for the mass loss of ice glaciers. However, other factors such as wind drift or the loss of ice chunks, which also play a role in the mass balance, can be excluded for rockglaciers because the thick debris cover protects the underlying permafrost body of a rockglacier against these

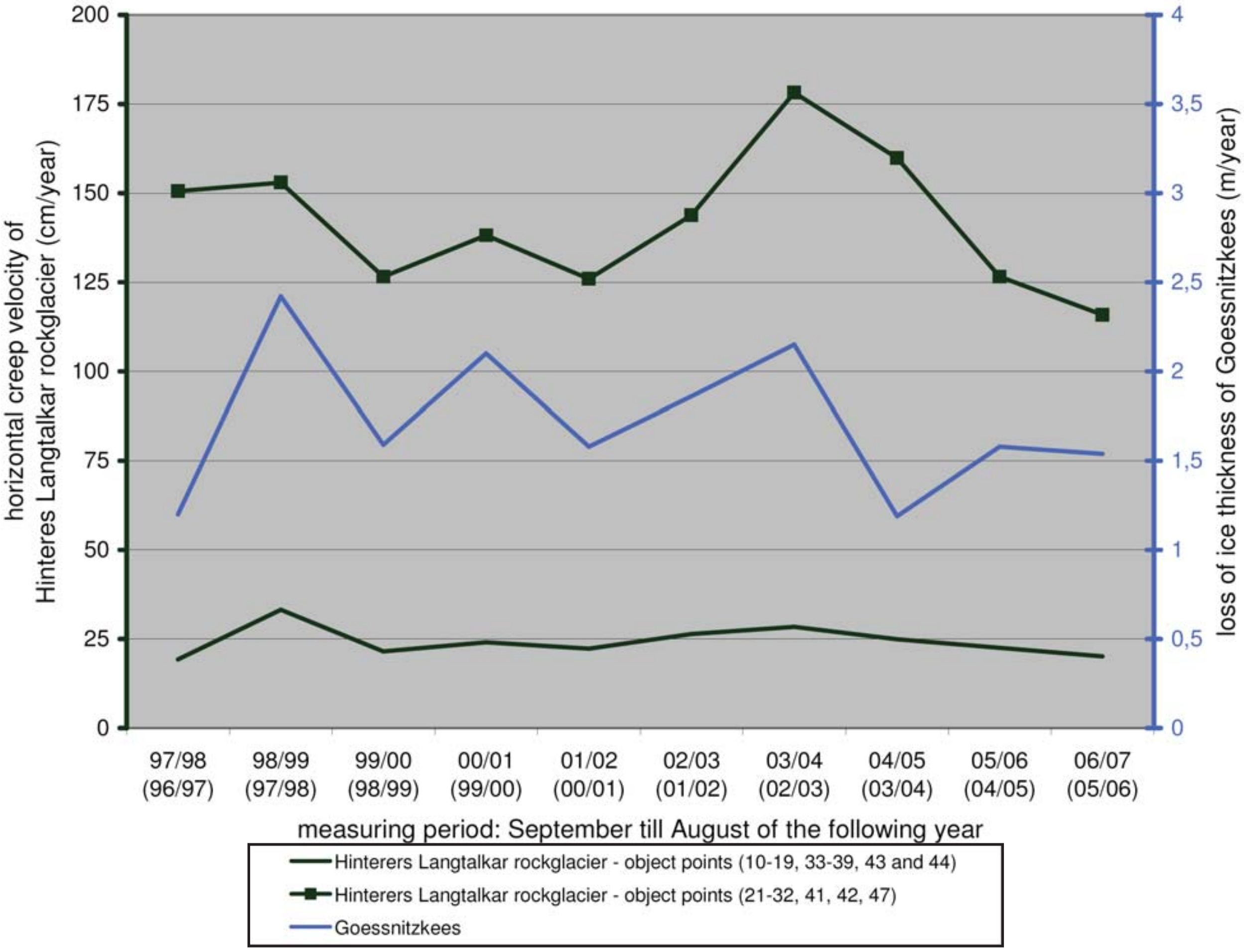


**Figure 7:** Comparison between the mean horizontal displacement rate of selected object points of the Hinteres Langtalkar rockglacier and mean annual ice thickness loss of the Goessnitzkees of the preceding year. Annotation: measuring year without a bracket = measuring year of the creep velocity; measuring year within a bracket = measuring year of the ice thickness change.

factors. One can assume that some of the unresolved questions can be or partly solved through the just mentioned factors. It might also be interesting to find out if the creep velocity of a rockglacier better correlates with the mean temperature of only those days with a temperature above 0°C since the values of the mass balance of ice glaciers highly correspond with the temperatures during the ablation period (Schöner et al. 2000).

## 6. Conclusion and perspective

Analysis has shown that the MAAT has an influence on the creep behaviour of rockglaciers. The horizontal displacement rates react with a delay of one year to the MAAT. According to my study, warm years entail greater and cold ones lower velocities. However, the vertical displacement rates seem to react quicker to the MAAT, which is shown in the mass loss of the permafrost body (= permafrost melt). Moreover, constant warm years have further accelerated the flow velocity in the lower and middle parts of the rockglacier (in two out of three cases). Furthermore, the relative change between the highest and smallest displacement rate generally increases from the slower to the faster object points. This finding points to the fact that small displacement rates are proportionally accelerated more quickly than already great ones.

However, there are a few measuring years in which certain groups with selected object points exhibit variations in their displacement rates that cannot be explained by the MAAT. For this purpose the Goessnitzkees has been consulted as an object of comparison. Much points to the fact that some unresolved questions concerning the creep behaviour could possibly answered by incorporating factors such as precipitation, MAGST, sublimation and/or ice as well as snow avalanches. Future studies must show which factors and to what degree they are responsible for the creep behaviour of rockglaciers. At some rockglaciers the MAGST has already been measured for couple of years. By installing little weather stations close to rockglaciers, as it has been done in the Hinteres Langtalkar, exact data can be collected on precipitation and air temperature which should bring further insight. For example it could give information about the number of frost days which certainly has an influence on the phenomenon rockglacier.

It will be interesting to see, how the surface velocities will have developed in the present year since the MAAT has reached its peak value in the measuring year 2006/07. According to this the displacement rates of the measuring year 2007/08 should have increased considerably, whereas the slower object points should have proportionally greater displacement rates than the faster ones since lower temperatures had been measured in the previous three years.

## References

AVIAN, M., KAUFMANN V. and LIEB, G.K., 2005: Recent and Holocene dynamics of a rock glacier system – the example of Langtalkar (Central Alps, Austria). In: Norsk Geografisk Tidsskrift/Norwegian Journal of Geography 59 (1), p. 1-8.

BUCK, S., 2008: Der Einfluss der Lufttemperatur auf das Fließverhalten von drei Blockgletschern in den Hohen Tauern. Examination thesis. Institute of Landscape Ecology, University of Münster.

DELALOYE, R., PERRUCHOUD, E., AVIAN, M., KAUFMANN, V., BODIN, X., HAUSMANN, H., IKEDA, A., KÄÄB, A., KELLERER-PIRKLBAUER, KRAINER, K., LAMBIEL, CH., MIHAJLOVIC, D., STAUB, B., ROER, I. and THIBERT, E., 2008: Recent Interannual Variations of Rock Glacier Creep in the European Alps. In: KANE, D.L. and HINKEL, K.M. (eds.) (2008): Proceedings of the Ninth International Conference on Permafrost, 29 June – 3 July 2008, Fairbanks, Alaska. Vol. 1, p. 343-348.

KÄÄB, A., 2005: Remote Sensing of Mountain Glaciers and Permafrost Creep. Zürich (= Schriftenreihe Physische Geographie. Glaziologie und Geomorphodynamik 48).

KÄÄB, A., FRAUENFELDER, R. and ROER, I., 2007: On the response of rockglacier creep to surface temperature increases. In: Global and Planetary Change 56 (1-2), p. 172-187.

KÄÄB, A., GUDMUNDSSON G. H., and HOELZLE, M., 1998: Surface Deformation of Creeping Mountain Permafrost. Photogrammetric Investigations on Rock Glacier Murtèl, Swiss Alps. In: LEWKOWIEZ, A. G. and ALLARD, M. (eds.) (1998): Permafrost. Seventh International Conference on Permafrost, Yellowknife, Canada, 23-27 June 1998. Québec, S. 531-537 (= Collection Nordicana 57).

KAUFMANN, V., LADSTÄDTER R. and KIENAST, G., 2007: 10 years of monitoring of the Doesen rock glacier (Ankogel group, Austria) - A review of the research activities for the time period 1995-2005. In: Petrovic, D. (ed.): Proceedings of the Fifth Mountain Cartography Workshop, 29 March - 1 April 2006, Bohinj, Slovenia, p. 129-144.

KAUFMANN, V., LADSTÄDTER, R. and LIEB, G.K., 2006: Quantitative assessment of the creep process of Weissenkar rock glacier (Central Alps, Austria). In: KAUFMANN V. and SULZER W. (Eds.) (2006): Proceedings of the Eighth International Symposium on High Mountain Remote Sensing Cartography, 20 – 27 March 2005, La Paz, Bolivia. Graz, p. 77-86 (= Grazer Schriften der Geographie und Raumforschung 37).

KELLERER-PIRKLBAUER, A., KAUFMANN, V., KROBATH, M., LIEB, G.K. and AVIAN, M., 2008: 10 Years of Monitoring the Rock Glacier Kinematic and Surface Temperature at Weissenkar Rock Glacier, Austria (1997-2007). In: EGU General Assembly 2008. Geophysical Research Abstracts, Vol. 10, EGU2008-A-02061.

KRAINER, K., 2005: Geologie. Nationalpark Hohe Tauern. 2nd edition, Klagenfurt (= Wissenschaftliche Schriften - Nationalpark Hohe Tauern).

LIEB, G.K., 1996: Permafrost und Blockgletscher in den östlichen österreichischen Alpen. In: LEITNER, W. (ed.) (1996): Beiträge zur Permafrostforschung in Österreich. Contributions to Permafrost Research in Austria. Graz, p. 9-125 (= Arbeiten aus dem Institut für Geographie der Karl-Franzens-Universität Graz 33).

LIEB, G.K, KAUFMANN, V. and AVIAN, M., 2004: Das Hintere Langtalkar (Schobergruppe, Nationalpark Hohe Tauern) – ein Beispiel für die komplexe Morphodynamik in der Hochgebirgsstufe der Zentralalpen. In: Mitteilungen der Österreichischen Geographischen Gesellschaft 146, p. 147-164.

MODIS., 2006: User Guide, http://tbrs.arizona.edu/project/MODIS/UserGuide_doc.php, -93.

ROER, I., AVIAN, M., DELALOYE, R., LAMBIEL, C., DOUSSE, J.-P., BODIN, X., THIBERT, E., KÄÄB, A., KAUFMANN, V., DAMM, B. and LANGER, M., 2005: Rock glacier "speed-up" throughout European Alps - a climatic signal? In: GEOUNION ALFRED-WEGENER-STIFTUNG (ed.) (2005): Second European Conference on Permafrost, 12-16 June 2005, Potsdam, Germany. Programme and Abstracts. Berlin, p. 101-102 (= Terra Nostra 2005 (2)).

ROER, I., HAEBERLI, W., AVIAN, M., KAUFMANN, V., DELALOYE, R., LAMBIEL, C. and KÄÄB, A, 2008: Observations and Considerations on Destabilizing Active Rock Glaciers in the European Alps. In: KANE, D.L. and HINKEL, K.M. (eds.) (2008): Proceedings of the Ninth International Conference on Permafrost, 29 June – 3 July 2008, Fairbanks, Alaska. Vol. 2, p. 1505-1510.

SCHNEIDER, B. and SCHNEIDER, H., 2001: Zur 60jährigen Messreihe der kurzfristigen Geschwindigkeitsschwankungen am Blockgletscher im Äusseren Hochebenkar, Ötztaler Alpen, Tirol. In: Zeitschrift für Gletscherkunde und Glazialgeologie 37 (1), p. 1–33.

SCHÖNER, W., AUER, I. and BÖHM R., 2000: Klimaänderung und Gletscherverhalten in den Hohen Tauern. In: Salzburger Geographische Arbeiten 36, p. 97-113.

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