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MULTIVARIATE STATISTICAL MODELLING OF EQUILIBRIUM LINE ALTITUDES: HINTEREISFERNER (ÖTZTAL) – STUBACHER SONNBLICKKEES (HOHE TAUERN)

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With 5 figures

ABSTRACT

Equilibrium line altitudes of Hintereisferner and Stubacher Sonnblickkees (Eastern Alps) are modelled from climatic data of Hoher Sonnblick (3106 m) and Marienberg (1335 m) using multiple linear regression equations. In the case of Hintereisferner, more than 100 years are covered by observed and modelled ELAs. The results of the regression analysis are compared with those obtained with a slightly modified glacial-meteorological model by Kuhn. Although multiple correlation coefficients are high (>0.9), it can be shown that the results from the regression model are only about 10 % better than those from the glacial-meteorological approach. For the modelling of longer periods of ELA fluctuations from climatic data covering periods with colder climate, a glacial-meteorological approach seems to be better suited, as it is more robust and physically more explicit.

MULTIVARIATE STATISTISCHE MODELLIERUNG DER HÖHE DER GLEICHGEWICHTSLINIE: HINTEREISFERNER (ÖTZTALER ALPEN) – STUBACHER SONNBLICKKEES (HOHE TAUERN)

ZUSAMMENFASSUNG

Mit Klimadaten vom Hohen Sonnblick (3106 m) und von Marienberg (1335 m) werden die Schwankungen der Gleichgewichtslinie von Hintereisferner und Stubacher Sonnblickkees modelliert. Dabei wird einerseits der glazialmeteorologische Ansatz von Kuhn in einer leicht modifizierten Form und andererseits die multiple Regressionsrechnung verwendet. Obwohl die Ergebnisse der multiplen Regressionsrechnungen um etwa 10 % besser sind ($r > 0.9$), sind ihre Ergebnisse oft schwierig zu interpretieren und zu verstehen. Für das Modellieren von längeren Perioden, die auch kältere Zeitabschnitte umfassen, sollte daher das Modell von Kuhn bevorzugt werden, da es robuster und physikalisch expliziter ist.

1. INTRODUCTION

In this paper the behaviour of the equilibrium line altitude (ELA) of Hintereisferner and Stubacher Sonnblickkees is modelled with the glacial-meteorological approach by Kuhn (1981, 1989) and with multiple regression equations, using climate data as independent variables. For that kind of modelling, the ELA is much better suited than the behaviour of glacier tongues. The ELA of a glacier reacts immediately on climatic fluctuations from year to year, whereas the reaction of a glacier tongues is influenced by numerous other factors, for example glacier size, glacier topography and the resulting behaviour of glacier flow (comp. Posamentier, 1977; Kuhn, 1978). As reliable climatic data from the Eastern

Alps are available since the late 19th century, it is possible to cover a period of about 100 years. This period includes the prominent glacier advance period of the 1920s, which may also serve as a model for the advance of the middle of the 19th century. Hintereisferner is a valley glacier in the central Ötztal Alps at the alpine main ridge, situated within a moderately continental climate, while Stubacher Sonnblickkees is a mountain glacier at the northern slope of the Hohe Tauern in a more maritime climatic environment (Fig. 1). A continuous record of observed ELAs exists for Hintereisferner since 1953, and, more reliably, since 1955. The years of 1961, 1962 and 1972 were not used, because the data are assumed to be unreliable for various reasons (Steinacker, 1979). For the Stubacher Sonnblickkees, a comparable record was published by Slupetzky (1989) for the period from 1959 to 1988. Data from 1989 to 1992 were taken from Slupetzky (1989–1993).

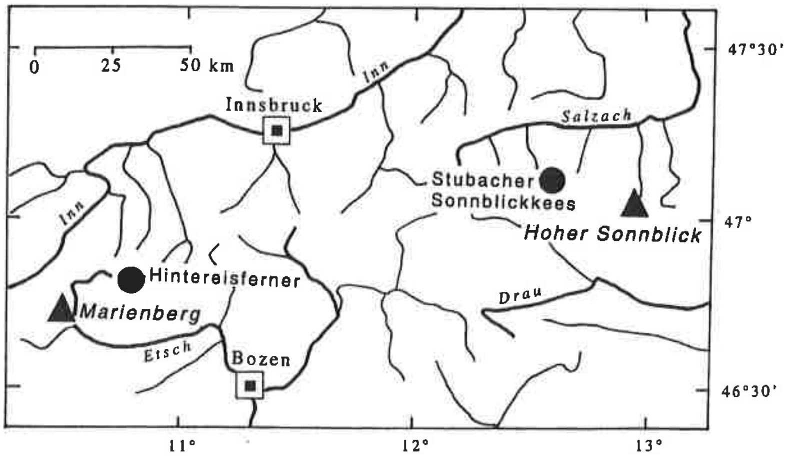

Fig. 1: Index map of glaciers and climatic stations

The climatic data used come from the Sonnblick observatory (temperature, vapour pressure, precipitation) and from Marienberg (precipitation). All these climatic data are easily obtainable. At the Hoher Sonnblick (3106 m), which is situated at the main ridge of the Hohe Tauern, daily climatic observations began in late 1886 and are continued since then (Auer et al., 1992; Böhm, 1992). Only three days of temperature data are missing (November 1919), while vapour pressure data are missing from September 1920 until August 1922. Daily measurements of precipitation started in 1891, but these data are inhomogeneous and unreliable due to the measurement problems on a mountain top and should not be used (Auer, 1992a). More reliable precipitation data are available from totalizer measurements since 1928 („Totalisator mit horizontaler Auffangfläche", Auer 1992b). Marienberg is a monastery in the upper Etsch valley (Vinschgau) in South Tyrol, situated a few kilometres south of the Reschen pass at 1335 m. There, precipitation measurements started in 1858 and are continued since then. An extensive treatment of the precipitation data of Marienberg was published by Fliri (1986). A thorough analysis of their usefulness for the analysis of glacier behaviour in the Ötztal region has been presented by Stuefer (1995).

Positive degree days were calculated from the daily mean temperatures $[(t_{min}+t_{max})/2]$ for every month from the Sonnblick data for altitudes of 2400 m, 2700 m and 3000 m (variables

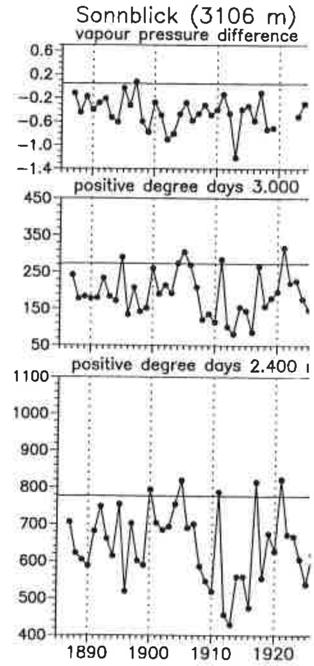

Fig. 2: Climatic varial

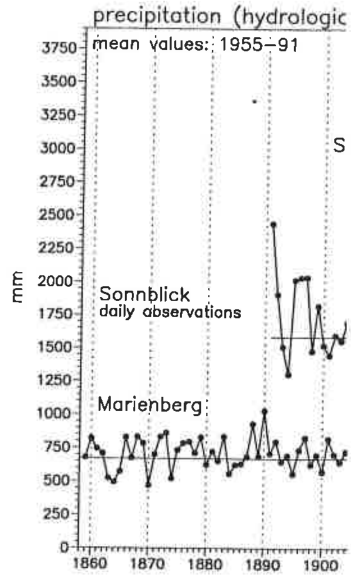

Fig. 3: Precipitation: Sonnblicl

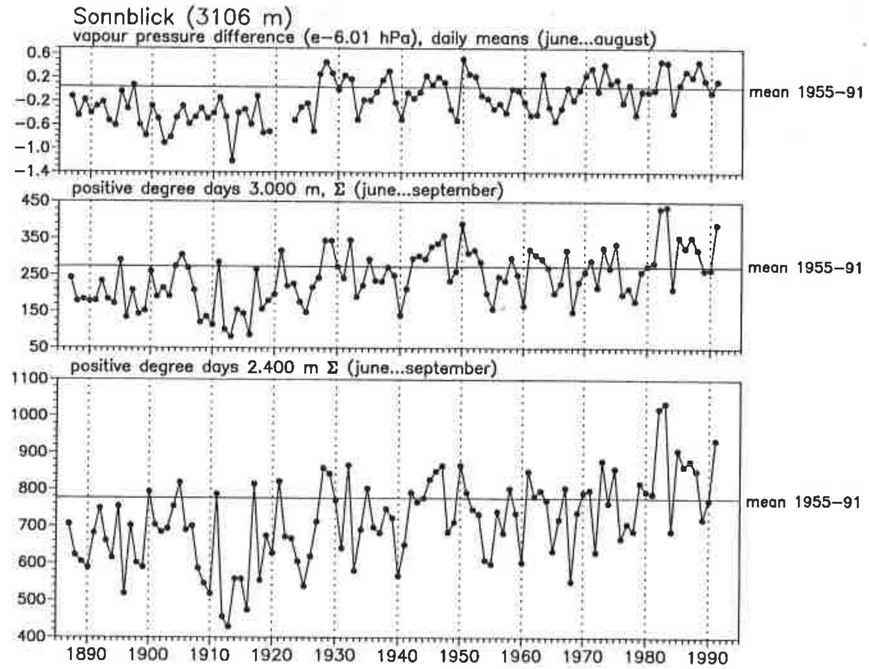

Fig. 2: Climatic variables, Sonnblick (3106 m), 1887–1991

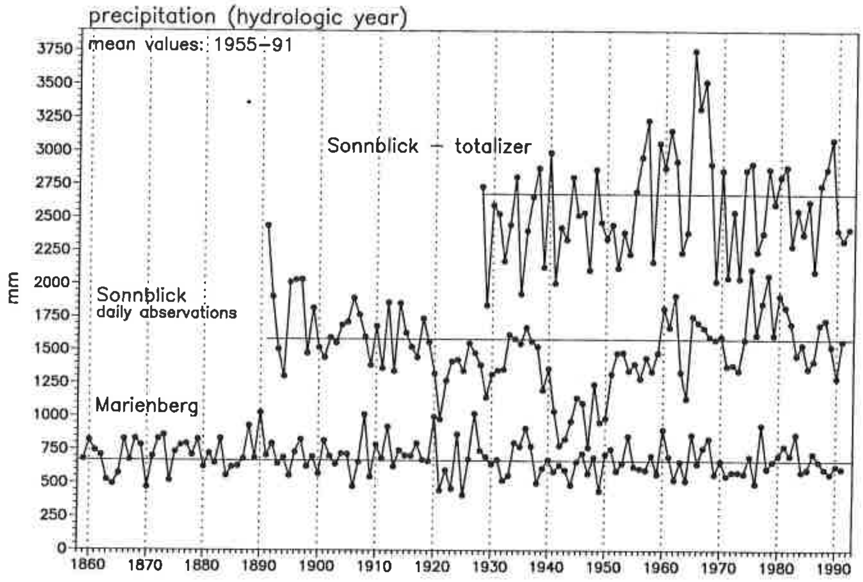

Fig. 3: Precipitation: Sonnblick (totalizer), Sonnblick (daily observations), Marienberg

$PDD24_{5-9}$, $PDD27_{5-9}$, $PDD30_{5-9}$). They were used for both glaciers, as temperature changes do not considerably vary with space (Böhm, 1992). Monthly precipitation sums from Marienberg (prMB) were used for Hintereisferner and the monthly sums from the Sonnblick totalizer (prST) were used for Stubacher Sonnblickkees. A first impression of the variability of temperature, vapour pressure differences (e – 6.1 hPa, variables $ediff_{5-9}$) and precipitation during the period 1859–1991 is provided by Figures 2 and 3. To get some idea about changes of the surface albedo, the number of days with fresh snow cover at 2700 m ($DFSC_{5-9}$) was also calculated from the Sonnblick data, assuming that 5 mm of precipitation fallen at temperatures below 1 °C at 2700 m are equivalent to two days of fresh snowcover. The calculation of this variable needs daily precipitation sums and is therefore subject to the measurement problems mentioned above. However, it does not show such a clear variability with time as the daily precipitation values do, so its use seems to be justified.

2. DETERMINISTIC MODELLING

The glacial-meteorological model by Kuhn (1981, 1989) for fluctuations of the ELA can be used as a first approximation for the behaviour of the ELA and as a reference for the success or failure of statistical modelling. In its most simple form, disregarding changes in the radiation balance, it reads

$$\delta h = (\alpha * \delta Ta - L/\tau * \delta c) / ((L/\tau) * (\partial c/\partial z) - \alpha * \delta Ta/\partial z)$$

δh	change of the ELA
Ta	mean temperature of the ablation season
c	accumulation
α	turbulent heat exchange coefficient (1.7 MJ m^{-2} d^{-1}
L	latent heat of fusion (0.334 MJ m^{-2} d^{-1})
τ	length of the ablation season (100 d)
$\partial Ta/\partial z$	vertical lapse rate of temperature (–0.0071 °C m^{-1})
$\partial c/\partial z$	vertical lapse rate of accumulation (1.5 kg m^{-1})

For both glaciers mean temperatures were taken from the Sonnblick data. Precipitation at Marienberg was used as a parameter for accumulation at Hintereisferner and the Sonnblick totalizer measurements were used for Stubacher Sonnblickkees. The mean temperatures and accumulation values were adjusted stepwise in such a way that the mean of δh is zero and that no correlation exists among the model error (ELA_{mod} – ELA) and the independent variables (in this case, monthly mean temperatures and monthly precipitation sums). Due to this process of empirical "fine-tuning", this application of Kuhn's model is somewhere in-between deterministic and statistical modelling.

To obtain the best results, mean temperatures have to be calculated for Hintereisferner as

$$Ta_{HEF} = (t_6 + t_7 + t_8 * 0.75 + t_9 * 0.25) / 3$$
mean (1955–1992, excluding 1961, 1962, 1972) = 0.85 °C

and for Stubacher Sonnblickkees as

$$Ta_{SSK} = (t_6 * 0.9 + t_7 + t_8 * 0.75 + t_9 * 0.15) / 2.8$$
mean (1959–1992) = 0.96 °C

In a similar way, the precipitation sums of Marienberg (prMB) are empirically adjusted for Hintereisferner as

$$c_{HEF} = (prMB_{10-9} + prMB_5 * 1.5 + prMB_7 * 0.5 + prMB_8 * 0.5) * 2$$
mean (1955–1992, excluding 1961, 1962, 1972) = 1728 mm

and for Stubacher Sonnblickkees the Sonnblick totalizer sums (prTS) as

$$c_{SSK} = prTS_{10-4} * 0.6 + prTS_5 * 0.3 + prTS_6 * 1.3 + prTS_7 * 0.9 + prTS_8 * 0.6 + prTS_9 * 1.8$$
mean (1959–1992) = 1996 mm

To achieve optimal results, temperature and accumulation deviations for Hintereisferner (1955–1991, excluding 1961, 1962 and 1972) are then calculated as

$\delta Ta_{HEF} = (Ta_{HEF} - 0.85) * 1.4$ (for $\delta Ta_{HEF} >= 0$)
$\delta Ta_{HEF} = (Ta_{HEF} - 0.85) * 1.2$ (for $\delta Ta_{HEF} < 0$)
$\delta c_{HEF} = (c_{HEF} - 1728) * 1.2$ (for $\delta Ta_{HEF} >= 0$)
$\delta c_{HEF} = (c_{HEF} - 1728) * 0.8$ (for $\delta Ta_{HEF} < 0$)

and for Stubacher Sonnblickkees (1959–1992)

$\delta Ta_{SSK} = (Ta_{SSK} - 0.96) * 0.8$
$\delta c_{SSK} = c_{SSK} - 1996$

The differential adjustment of δTa and δc for Hintereisferner brings a clear improvement of the correlation among observed and modelled ELAs. Probably it takes those factors into account, which are not sufficiently covered by temperature, e.g. changes in the surface albedo as well as uncertainties in the value of α. At Stubacher Sonnblickkees, the necessary adjustment of δTa could perhaps also reflect the influence of topography.

The results of this kind of modelling are surprisingly good. The correlation coefficient between the observed and modelled ELA is 0.884 for Hintereisferner (78 % of the variance explained) and 0.855 for Stubacher Sonnblickkees (73 % of the variance explained). These correlation coefficients are used as benchmarks for the regression modelling.

3. REGRESSION MODELLING

In a regression model, changes of the dependent variable (ELA) are related to changes of the independent variables (climatic data). Although this is a stochastic technique, the climatic data chosen should be physically meaningful (Kuhn, 1993). However, the results must not be interpreted in a strict physical sense, because variables may actually carry some unknown "hidden" information. So, for example, positive degree days may also provide information about the radiation balance, although radiation balance is not explicitly included among the variables. One of the most serious problems which may occur when climatic data are used, is multi-collinearity. This describes the effect of a high correlation (or physical interdependece) among independent variables, e.g. vapour pressure differences and temperature. This could be partly overcome if a principal component analysis of the climatic data were made, but this would make interpretation of the results even more difficult. To account for possible non-linear effects, squared values (sq) for positive degree days and days with fresh snow cover were also included in the calculations.

Modelling always started with a standard set of physically reasonable variables ($PDD24_{5-9}$, $PDD27_{5-9}$, $PDD30_{5-9}$, $PDD30_{5-9}$ sq, $Prec_{10-4}$, $Prec_{5-9}$, and, alternatively, $ediff_{5-9}$ or $DFSC_{5-9}$, $DFSC_{5-9}$ sq). Then, data selection was done by the software (SPSS/PC+). The regression routine of SPSS provides several procedures for the inclusion or exclusion of independent variables according to their significance. In any case, an optimisation of the multiple correlation coefficient is attempted by the software. The general form of such an equation is in this case

$$ELA = constant + B1 * V1 + B2 * V2 + \ldots Bn * Vn + error$$

where the regression coefficient Bn is the weight of the variable Vn. To get an idea about the relative importance of the variables, the standardised regression coefficient β can be used. It shows by how many standard deviations the dependent variable changes, if the respective independent variable changes by one standard deviation. This coefficient can, however, be misleading, if combined effects are neglected.

The best results could be obtained for Hintereisferner with an equation using the following variables:

Variable	B	β	signif.
$prMB_{10-5}$	–.18	–.14	.172
$prMB_8$	–.55	–.18	.046
$DFSC_6$	–28.7	–1.21	.006
$DFSC_6$ sq	.525	.69	.113
$DFSC_9$	–19.9	–1.07	.013
$DFSC_9$ sq	.795	1.09	.010
$PDD30_7$	6.50	1.74	.001
$PDD30_7$ sq	–.023	–1.42	.005
$PDD24_8$	1.36	.53	.000
$PDD24_9$	1.51	.58	.108
$PDD30_9$ sq	–.018	–.48	.038
Constant	2625		.000

The multiple correlation coefficient is 0.93 with 87 % of the variance explained. Compared with the modified Kuhn model, the net gain in explained variance is 9 %, which is not very much.

For Stubacher Sonnblickkees, a similar approach gives the following results:

Variable	B	β	signif.
$prTS_{10-5}$	–.14	–.42	.001
$prTS_6$	–.58	–.47	.000
$prTS_7$	–.42	–.32	.016
$prTS_8$	–.37	–.27	.051
$prTS_9$	–.40	–.35	.002
$PDD24_6$	.87	.22	.043
$PDD24_7$	–2.71	–1.09	.072
$PDD30_7$	4.22	1.24	.037
$PDD24_8$	–5.25	–2.11	.005
$PDD30_8$	11.53	3.35	.001
$PDD30_8$sq	–.02	–1.05	.027
Constant	3825		.000

The multiple correlation coefficient is 0.92 with 85 % of the variance explained. The net gain in explained variance, compared with the modified Kuhn model, is 12 %, which is about the same as for Hintereisferner. It is interesting to see that the behaviour of the ELA of Stubacher Sonnblickkees depends to a greater extent on precipitation-related variables while the ELA of Hintereisferner is more influenced by ablation-related variables. In both cases, vapour pressure differences are so highly correlated with temperature that they could not be used.

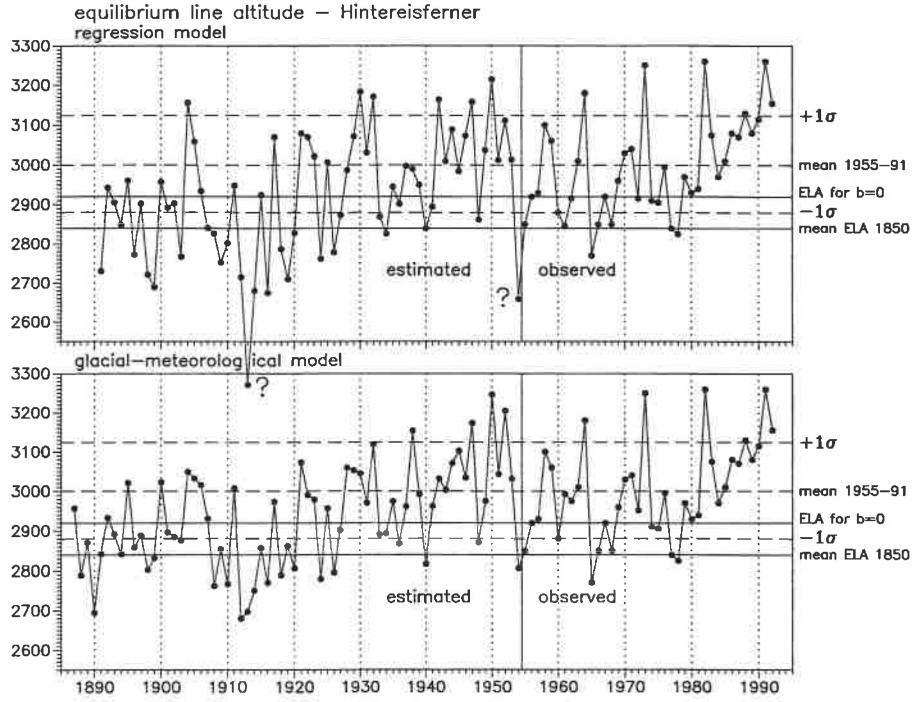

Fig. 4: Equilibrium line altitudes, Hintereisferner

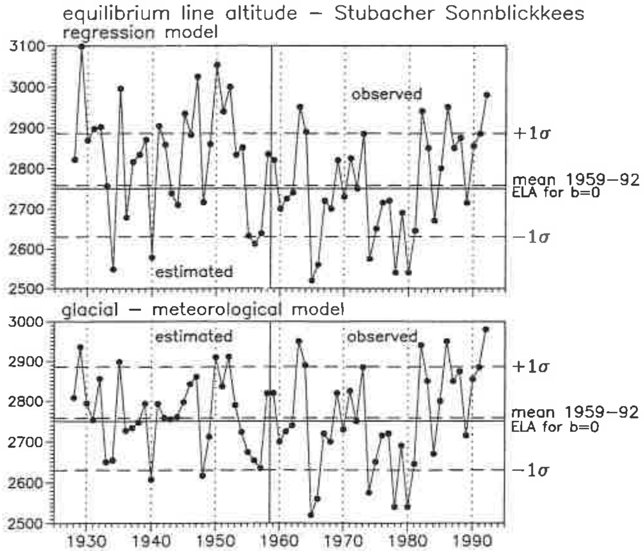

Fig. 5: Equilibrium line altitudes, Stubacher Sonnblickkees

Extrapolation back in time with these models is somewhat limited (Fig. 4 and 5). In a strict sense, it is not permitted to do so beyond the limits of the independent variables in the original data set. As most of the input data come from fairly warm years, the applicability of the models is therefore limited to periods with warm conditions. Additionally, the statistical error of extrapolation increases hyperbolically with the distance from the common mean values of the independent variables. If an extrapolation is made to much colder periods dominated by different synoptic conditions, e.g. to the years before World War I, some unexpected results can occur, although the general tendency should be seized well. This is to a greater extent true for Hintereisferner, because its ELA can be modelled back to 1891, while modelling of the ELA of Stubacher Sonnblickkees is limited with the year of 1928, when climatic conditions were already rather similar to those of the last decades. So, for example, an unrealistically low ELA of Hintereisferner is predicted for 1913 and the predicted ELA for 1954 seems to be unrealistically low as well.

In any case, Figure 4 shows that the ELA of Hintereisferner was very low during the years preceding the early 1920s, and that it was probably much lower than the mean ELA of the 1850-advance. The climatic conditions during this period might have led to a similar glacier extent as during the middle of the 19th century, if they had lasted for some more years (Patzelt, 1973).

4. CONCLUSIONS

Compared with the results of the modified Kuhn Model, those obtained with multiple regression equations are about 10 % better. The results of the regression analysis are, however, difficult to interpret from a physical point of view and, due to statistical reasons, of only limited value for extrapolation back in time towards more colder periods. For paleoglaciological modelling of the recent past, when climatic data from the surrounding areas are available, more deterministic models should therefore be preferred. Regression equations are a useful tool, if climatic data from more remote stations or proxy data are used as independent variables.

In any case it can be shown that temperature data from the Sonnblick observatory are useful variables for describing ablation conditions over large areas of the Eastern Alps. The Sonnblick totalizer sums can be adapted as accumulation data for the Northern Hohe Tauern region and the precipitation data from Marienberg provide reasonable information about the accumulation conditions in the central Ötztal Alps.

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