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FLUCTUATIONS OF CLIMATE AND MASS BALANCE: DIFFERENT RESPONSES OF TWO ADJACENT GLACIERS

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With 4 figures

SUMMARY

The response of two adjacent glaciers in the central Eastern Alps to climatic variations was observed in terms of length for 60 years and of mass balance for 30 years. Their differing behavior is analysed and explained by topography, area/altitude distribution, different dynamic response times and to a lesser degree by methodical difficulties.

KLIMASCHWANKUNGEN UND MASSENBILANZ: VERSCHIEDENE REAKTIONEN ZWEIER BENACHBARTER GLETSCHER

ZUSAMMENFASSUNG

Die Reaktionen zweier benachbarter Gletscher in den Ötztaler Alpen auf Änderungen in Klima und Witterung werden anhand einer 60jährigen Reihe von Längenmessungen und 30 Jahren Massenbilanzbestimmungen untersucht. Ihr verschiedenes Verhalten wird mit Topographie, Flächen-Höhen-Verteilung, verschiedenen dynamischen Reaktionszeiten und zu einem geringeren Teil mit methodischen Unstimmigkeiten erklärt.

1. INTRODUCTION

Advances or retreats of glaciers have often been used to reconstruct the climatic fluctuations causing them. Changes in precipitation and wind will lead to changes in accumulation, while changes in temperature and radiation fluxes, among other factors, will affect the surface energy balance and thus ablation. These mass balance disturbances in turn alter the flow regime of the glaciers such that they approach a new areal and altitudinal extent in which accumulation and ablation are in balance again. From these changed dimensions the preceeding climatic variations are inferred by various models or, more often but less reliably, by simple qualitative arguments.

This paper discusses the different reactions of two neighbouring alpine glaciers to the same climatic forcing over the past 30 years. Hintereisferner (9 km^2) and Kesselwandferner (4 km^2) are situated in the center of the Ötztal Alps at approximately 10° 50′ E and 46° 50′ N, in one of the driest zones of the Eastern Alps. Presently they extend from about 3750 to 2450 m and 3500 to 2600 m, respectively. Their lower parts are sketched in fig. 1 which also shows their extent at various years in the past. While they shared a tongue of 1.5 km in 1847 they separated after the advance of 1920 and

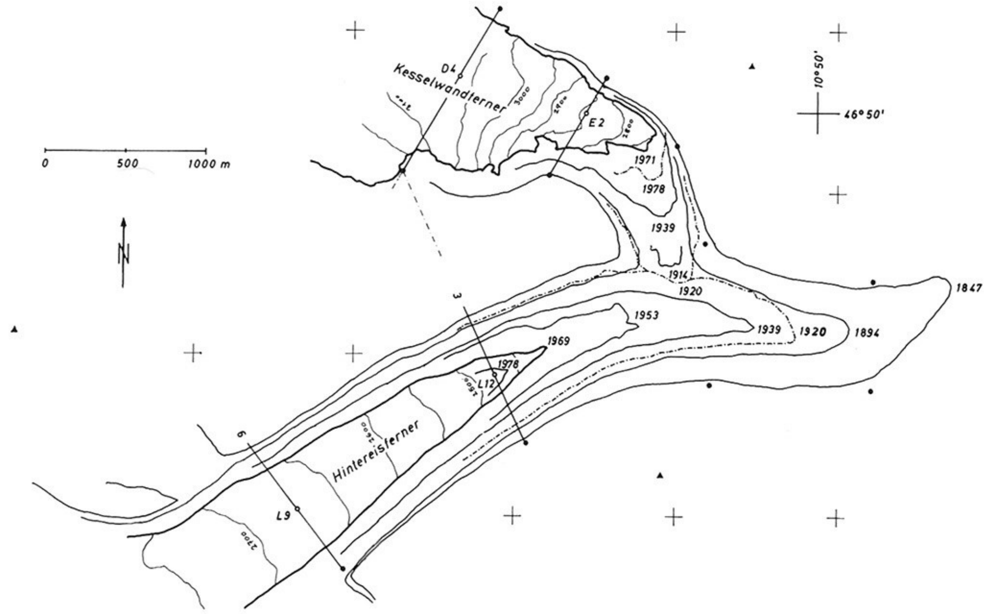

Fig. 1: The tongues of Hintereisferner and Kesselwandferner and their extent in various years in the past

Table 1: Summary of glaciological and topographic characteristics of Hintereisferner and Kesselwandferner (1952—1982)

		Hintereisferner	Kesselwandferner
Total area S	km²	9.34	4.13
Ablation area, S_a		3.86	1.05
Accumulation area, S_c		5.48	3.08
S_c/S		0.59	0.75
Highest elevation	m	3739	3500
Lowest elevation		2450	2600
Median altitude		3050	3200
Altitude of largest area increment		3100—3150	3200—3250
Mean equilibrium line altitude, h		2970	3090
Mean altitude of ablation area, z_a		2750	2850
Aspect of tongues		NE	SE
Length of central flow line	km	7.1	4.5
Annual mean specific balance, $\bar{b}$	kg m^{-2}	− 260	+70
Mean specific winter balance, $\bar{b}_w$		1630	—
Mean balance of ablation area, b_a		−1590	−1820
Mean balance of accumulation area, b_c		670	720
Mean balance gradient of ablation area $b_a/(z_a - h)$	kg m^{-2}m^{-1}	7.2	7.6
Mean balance gradient of lowest 300 m		1.0	1.7

are now about 1.5 km apart. Their most relevant glaciological and topographic characteristics are summarized in table 1.

The two glaciers have been studied extensively since 1952. Mass balances were determined by the direct glaciological method, repeatedly checked by geodetic surface comparisons. Extent and velocity were surveyed annually with few exceptions. There is a climate station 10 km downvalley at 1900 m, a net of 12 rain gauges and seasonal records of thermohygrographs at 2400 and 3030 m.

2. OBSERVATIONS

As indicated in fig. 1 and table 1, respectively, the length and mass balance of the two neighbours follow different trends. This is amplified in figs. 2 and 3 which respectively show cumulative mean specific balances and variations of glacier lengths. In the period from 1952 to 1964 both glaciers had a net loss of mass, followed by a period of recovery till 1968. Hintereisferner reached a new minimum in 1976, briefly recovered in 1977 and 1978 and has since been losing mass. Kesselwandferner did not appreciably change from 1968 to 1973 when it again started gaining mass to reach its maximum in 1981, 2800 mm thicker, on the average, than it had started in 1952.

The mass loss till 1964 on both glaciers caused their tongues to shrink till 1966, when Kesselwandferner started reacting to the reversal of the mass balance with an

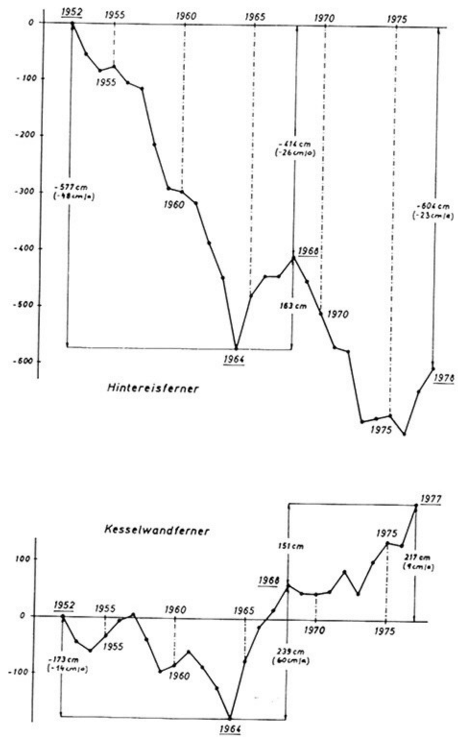

Fig. 2: Cumulative mean specific mass balances, in cm of water equivalent

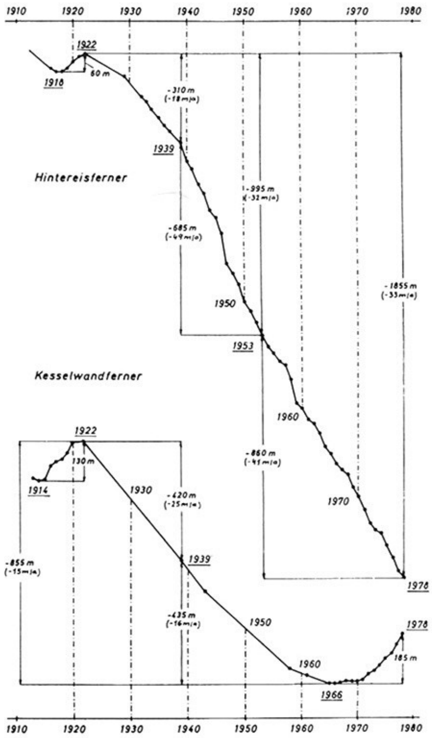

Fig. 3: Variations of glacier lengths

accelerating advance (fig. 3). Hintereisferner in turn continued its retreat to the beginning of the eighties when its terminus at last stagnated and at places showed signs of vitality with overriding ice wedges.

Table 2 suggests that summer temperatures and winter precipitation are among the variables determining the glacier mass balances. There is no doubt that more complex variables and processes have to be taken into account for a quantitative formulation of the climate/mass balance relationships (cf. Kuhn 1981). It is, however, not our intention to go into these details here, but rather to discuss the possible causes for the

Table 2: Average temperatures and precipitation at Vent (1900 m) and net mass balance of Hintereisferner for selected periods

Cumulative mass balance of Hintereisferner	1952—1964 12 years loss	1965—1968 4 years gain	1969—1976 8 years loss	1977—1981 5 years gain	1982—1983 2 years loss
T 1. 10.—30. 9.	1.4	1.3	1.3	1.4	2.2
T 1. 5.—30. 9.	7.8	7.2	7.5	7.2	9.0
P 1. 10.—30. 9.	635	720	620	680	630
P 1. 10.—31. 5.	310	330	295	400	380

diverging behavior of Hintereisferner and Kesselwandferner. These are believed to be

Different topography
Different dynamic response time
Inadequate representation of data

3. EFFECTS OF TOPOGRAPHY IN THE STATIONARY CASE

In order to judge the individual importance of these factors it is appropriate to recall the concept of steady state (Finsterwalder 1897). In the steady state the annual net accumulation submerges in the accumulation area, an equivalent amount flows through the cross section under the equilibrium line and replaces what has melted in the ablation area so that the glacier surface remains stationary. If S denotes area, b specific mass balance, and the indices c, a refer to accumulation and ablation area, respectively, in a stationary glacier

$$S_c \cdot b_c = -S_a \cdot b_a \tag{1}$$

that is, net accumulation equals net ablation.

Obviously a glacier with a relatively large accumulation area like Kesselwandferner needs high values of net ablation ($-b_a$) compared to b_c in order to fulfill the balance expressed in equation 1, which is confirmed by the comparison of Hintereisferner and Kesselwandferner in table 1.

Experience shows that most alpine glaciers have a nearly linear balance gradient

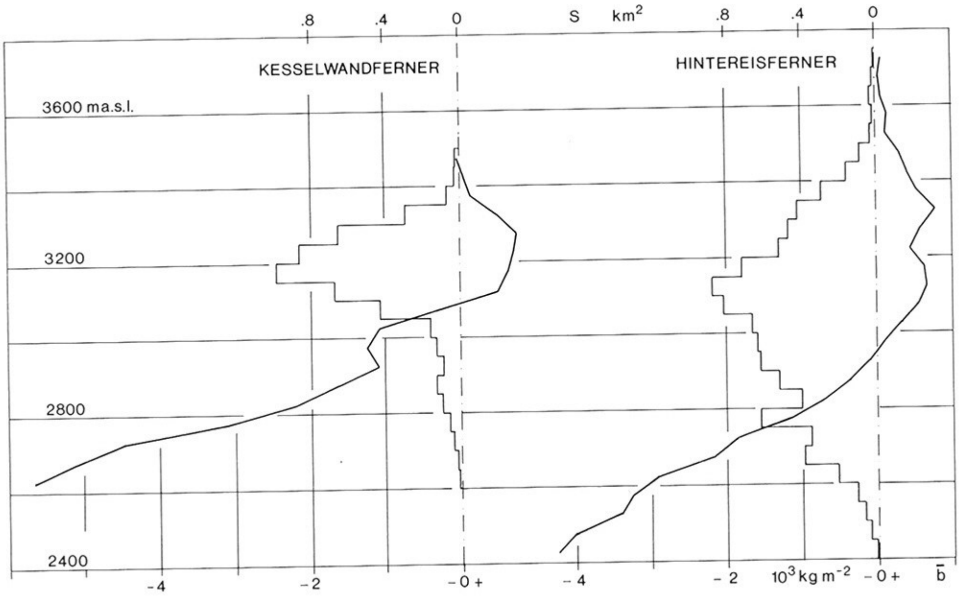

Fig. 4: The distribution with altitude of area S and specific mass balance, mean values 1979—81

db/dz in their ablation areas (fig. 4). Since $b = 0$ by definition at the altitude h_0 of the equilibrium line,

$$b(z) = db/dz\,(z - h_0). \tag{2}$$

Continuing the argument above we realize that a large accumulation are ratio $S_c/(S_c + S_a)$ must be accompanied by a large balance gradient in stationary glaciers: By virtue of its topography, Kesselwandferner has a large, plateau-like accumulation basin where plenty of drift snow is accumulated, and a steep tongue of southerly aspect resulting in a large balance gradient. In contrast, Hintereisferner is a relatively uniform valley glacier of moderate mass turnover and consequently lesser balance gradient than Kesselwandferner (table 1).

While this is true for the steady state, equations 2 and 3 are also helpful in understanding the response of the glaciers to climate fluctuations. A given change in accumulation δb_c is amplified by the area ratio

$$\delta b_a = -S_c/S_a\,\delta b_c \tag{3}$$

and for a given db/dz (which changes little with δb_c) the average altitude of the ablation area, according to equation 2 and 3 changes as

$$\delta z_a = \frac{\delta b_a}{db/dz} + \delta h = -\frac{S_c/S_a}{db/dz}\delta b_c + \delta h \tag{4}$$

where the adjustment of the equilibrium line altitude δh is the same for both glaciers. The amplification factor $(S_c/S_a)/(db/dz)$ in equation 4 is 0.20 m per (kg m^{-2}) for Hintereisferner and 0.39 for Kesselwandferner. In other words, the terminus of Kesselwandferner adjusts to a new equilibrium with twice the altitude change that is needed for Hintereisferner.

4. DYNAMIC RESPONSE

In 1965 ice flow was at a minimum on both glaciers (15 m a^{-1} in profile 6 on Hintereisferner, 35 m a^{-1} in profile D on Kesselwandferner, see fig. 1). With the mass balance increasing in the subsequent years both glaciers picked up speed. According to Nye's theories (Paterson 1981) a mass balance disturbance travels down a glacier with four times the mean ice velocity. By 1980 this thrust had not reached the terminus of Hintereisferner but had accelerated the terminus of smaller Kesselwandferner to nearly 100 m a^{-1}. This is one kind of dynamic response that contributed to the different length variations in the two glaciers (fig. 3).

5. BIASED MASS BALANCE DETERMINATION

In order to become independent of such dynamic effects, one generally prefers to study mass balance rather than glacier length variations. This principle needs no further explanation but it must be stressed here that mass balance, too, is influenced by the transient adjustment to present climatic conditions.

Mean specific mass balance is an average value for the entire glacier surface which may include large fractions that are remnants of previous advances. Hintereisferner for instance has lost more than 1 km^2 from 1958 to 1964. Applying the specific balance curve $b(z)$ of 1964 to the area $S(z)$ of 1958 results in a value of $\bar{b}$ lower by 65 kg m^{-2} than with actual size. In other cases this procedure simulated values of $\Delta\bar{b}$ of up to -140 kg m^{-2} which in some instances also changed the sign of $\bar{b}$. For Kesselwandferner this effect has become of significance only since its recent advance. Both glaciers thus give evidence to a minor bias which makes the mean specific mass balance of larger glaciers more negative than they would be if the glaciers had reached equilibrium sizes.

6. NATURAL MASS BALANCE DIFFERENCES

Since Kesselwandferner has only 17 % of its total area below 3050 m while Hintereisferner has 51 %, that part of the year when ablation is restricted to altitudes below 3050 m is of crucial importance for natural differences in their respective mass balance. The summer of 1982 may serve as an example:

At the station Vent (1900 m) the period May—August was one of the warmest on record. Vigorous melting on the respective tongues was more effective on Hintereisferner than on Kesselwandferner, yielding $\bar{b}$ (Hintereisferner) $= -1240$, $\bar{b}$ (Kesselwandferner) $= -620$ kg m^{-2}. In the extremely positive year 1976/77 little melting during summer rendered similar balances for both glaciers ($\bar{b}$ [Hintereisferner] $= +760$, $\bar{b}$ [Kesselwandferner] $= +700$ kg m^{-2}).

7. CONCLUSION

The topography or area/altitude distribution thus is the most important factor determining the different variations of mass balance and length of Hintereisferner and Kesselwandferner. The slower dynamic response of the large glacier and waves travelling along Kesselwandferner contribute significantly while methodical reasons play only a minor role.

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