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GLACIER VARIATION AND WEATHER

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Abstract. Statistical results of measurements of glacier variations in Switzerland 1891–1965 are compared with deviations from average temperature and precipitation in summer for stations above 2 000 m. The result is interpreted in terms of meso-scale glacier–weather relations. A correlation between glacier mass budget and deviation from the average height of the 500 mbar surface indicates the importance of cyclonic and anticyclonic conditions during the ablation period, and therefore of the frequency of certain *Grosswetterlagen* which has been studied for the period 1881–1965. The pattern of the difference of *Grosswetterlagen* favourable and unfavourable for glaciers resembles the pattern of glacier variations and also of mass-budget data. Atmospheric circulation in zonal and meridional forms, as expressed by the frequency of *Grosswetterlagen* has to be considered by seasons. There is no simple relation between the intensity of zonal circulation and glacier variation. Glacier recession of the last few decades seems to be caused by the fact that meso-scale weather conditions mainly in the ablation season have become much less cyclonic than in the decades 1886–95 and 1906–15.

Résumé. *Variation des glaciers et temps.* Les résultats statistiques des mesures des variations des glaciers suisses entre 1891 et 1965 sont comparés aux déviations de la température et des précipitations moyennes en été pour les stations au-dessus de 2 000 m. Le résultat est interprété selon les relations glacier–temps à l'échelle moyenne. Une corrélation entre le bilan de masse des glaciers et la déviation de l'altitude moyenne de la surface de 500 mbar indique l'importance des conditions cycloniques et anticycloniques pendant la période d'ablation, et ainsi de la fréquence de certains situations météorologiques générales étudiées pour la période 1881–1965. L'allure de la différence des situations météorologiques générales favorables ou non aux glaciers ressemble à l'allure des variations des glaciers et ainsi aux données de bilan de masse. La circulation atmosphèrique sous formes zonales et méridionales, exprimée par la fréquence des situations météorologiques générales, doit être considérée par saisons. Il n'y a pas de relation simple entre l'intensité de la circulation zonale et la variation des glaciers. La récession des glaciers des dernières décades semble être causée par le fait que les conditions météorologiques à l'échelle moyenne principalement pendant la saison d'ablation sont devenues bien moins cycloniques que pendant les décades 1886–95 et 1906–15.

Zusammenfassung. *Gletscherschwankungen und Witterung.* Statistische Ergebnisse von Messungen der Gletscherschwankungen in der Schweiz 1891–1965 werden mit Abweichungen vom Mittelwert von Temperatur und Niederschlag im Sommer an Stationen oberhalb von 2 000 m Höhe verglichen. Das Ergebnis wird mit den Beziehungen zwischen Gletscher und Witterung interpretiert. Eine Korrelation zwischen Massenhaushalt der Gletscher und Abweichungen von der mittleren Höhe der 500 mbar-Fläche deutet auf die Wichtigkeit zyklonaler oder antizyklonaler Witterungsbedingungen während der Ablationsperiode. und damit auf die Häufigkeit von bestimmten Grosswetterlagen, die für den Zeitraum 1881–1965 studiert wurde. Der Verlauf der Differenz von gletschergünstigen und gletscherungünstigen Grosswetterlagen ähnelt dem Verlauf der Gletscherschwankungen und der Massenhaushaltszahlen. Die atmosphärische Zirkulation in zonaler und meridionaler Form, wie sie durch die Häufigkeit der Grosswetterlagen angegeben wird, muss nach Jahreszeiten getrennt berücksichtigt werden. Es besteht jedenfalls keine einfache Beziehung zwischen der Intensität der zonalen Zirkulation und den Gletscherschwankungen. Der Gletscherrückgang während der letzten Jahrzehnte erscheint durch den Umstand verursacht, dass der Witterungscharakter vorwiegend in der Ablationsperiode viel weniger zyklonal war, als in den Jahrzehnten 1886–95 und 1906–15.

Variations of glaciers are closely related to variations in the weather conditions, as stated probably for the first time by Walcher (1773). This general statement has neither been seriously challenged nor has it been proved satisfactorily. This is partially due to a lack of adequate data, both meteorological and glaciological. What we ought to know is the amount of solid precipitation deposited during a budget year on a glacier or in a glacierized catchment area, and the heat budget of that area for the same time. Knowing this for a period of considerable length, the mass budget of a glacier could be analysed as a function of atmospheric conditions. Finally, the far more complex relation between advance and retreat of the glacier front and the variations in the climatic environment could be approached. Unfortunately there are only short-period investigations of the heat budget for small areas of a few selected glaciers available, and only very few short series of mass budget investigations for single glaciers. Regular meteorological observations from glacierized altitudes are scarce even in the Alps, and regular observations of advance or retreat of selected glacier fronts were initiated only after 1880 by the Schweizerische Gletscherkommission, to be followed soon by similar observations in other parts of the Alps and, due to the initiative of the Commission Internationale des Glaciers, since 1895 also in other parts of the globe. As, in the present writer's opinion, only results of observations should be used in the first instance as a basis for any attempt to analyse relations between glacier behaviour and weather, the contents of this paper will be essentially restricted to data of about the last 80 years.

Recently Kasser (unpublished) gave a critical statistical evaluation of the results of annual measurements of variations in length of glaciers in Switzerland for the period 1891 to 1965 (Fig. 1). Even though this series is not homogeneous either with respect to the number of observed glaciers or to the quality of observations, it is a unique document which deserves careful consideration, so much the more as the course of glacier variations in other parts of the Alps is very similar, as has been shown e.g. by Klebelsberg (1943) in a summary report for the years 1911 to 1941. The series commences in the middle of the 1890 advance, which came to an end in about 1901. Around 1906 the well-known period of glacier advance begins, culminating between 1916 and 1920, with almost 75 per cent of the observed glaciers participating. In 1926 for the last time 50 per cent of the observed glaciers were reported advancing. There follows a long period of glacier recession, down to the minimum in 1947 with all observed glaciers retreating. In 1955 a temporary tendency to advance was reported for 25 per cent of the glaciers under observation, and the same percentage of advancing glaciers was observed again in 1965 according to Kasser (1966). In 1966 this tendency continued with 34 out of 96 observed glaciers in Switzerland advancing (personal communication from P. Kasser). It has to be borne in mind, however, that this is a purely qualitative description of glacier behaviour. It is well known that single glaciers respond to a change in atmospheric conditions with a different time-lag, depending on the size and on other characteristics of the glacier, as suggested in the contribution to a discussion by Zingg ([U.G.G.I.], 1963, p. 84–85). Nevertheless, a sufficiently large number of glaciers under observation will exhibit the general tendency correctly. The glacier advance culminating around 1920 is the only one which can be

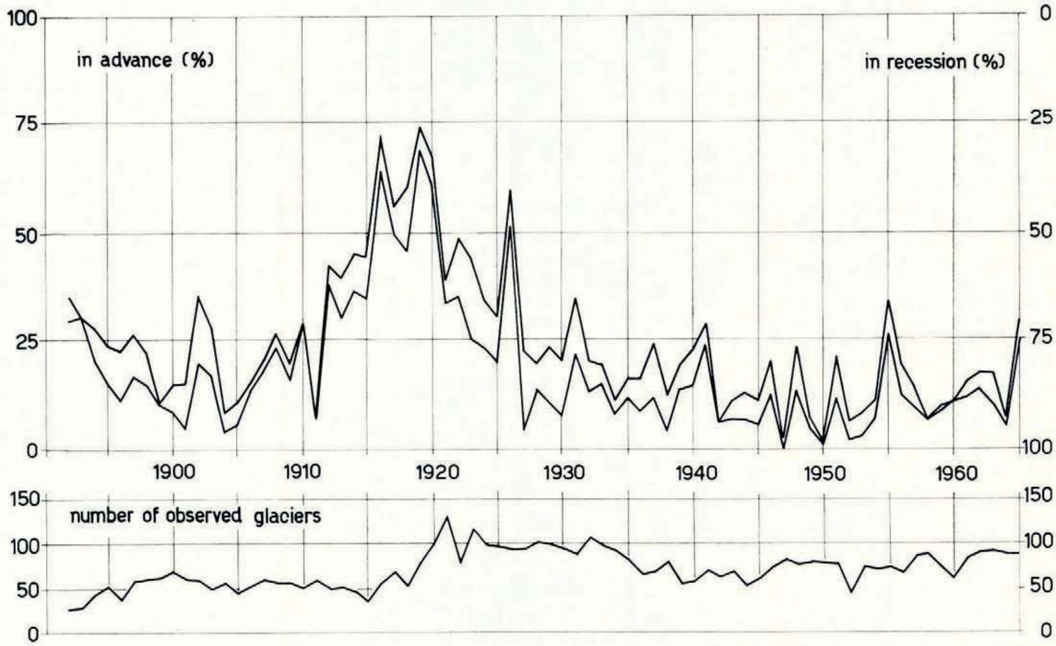

Fig. 1. Frequency in per cent of advancing, retreating and stationary glacier fronts in Switzerland 1891–1965. From Kasser (unpublished), completed

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followed by at least simple glaciological observations, thus giving some idea of how long it takes for the majority of alpine glaciers to react to given fluctuations of climatic elements.

The most easily available meteorological data are temperature and precipitation, which in summer can be considered as a substitute for radiation and albedo (Hoinkes, 1955). Only stations above 2 000 m altitude were used, viz. Obir 2 044 m (since 1944 replaced by Villacher Alpe 2 135 m), St. Gotthard 2 095 m, Grosser St. Bernhard 2 479 m, Säntis 2 500 m, Zugspitze 2 962 m, Sonnblick 3 106 m, and Jungfraujoch 3 576 m.* As can be seen from Figure 2 there is a good agreement between the five-yearly overlapping mean deviations from the 1851–1950 average of temperature and precipitation in summer with the fluctuations of glaciers. Coincident negative deviation of temperature and positive deviation of precipitation in summer clearly correspond to a tendency of glacier advance (Billwiller, 1931). In the series of five-yearly overlapping mean deviations of the above mentioned stations this is the case in 1889–96, 1908–18, 1924–25, and 1955–56 (1955 means average for 1953–57). The agreement between both curves is better for the five-yearly than for the ten-yearly overlapping means of deviations which have been published by Rudloff (1964) back to the year 1818.

The relation between glacier variations and mean annual temperature or the summer–winter range of temperature is not so good as demonstrated for instance by means of the temperature series of Vent, 1 900 m a.s.l. which has been compiled by Lauffer (unpublished) for the period 1851–1960. As can be seen from Figure 3 the coldest period around 1890 was cold in all seasons, foremost in winter, and the warmest period around 1950 likewise warm in all seasons, foremost in spring. Both periods with advancing glaciers had a negative deviation of summer temperature in common, whereas winters were coldest around 1890 and warmest around 1920, and mean annual temperature was very low around 1890, but close to average around 1920. The same was true over wide parts of Europe, according to Rudloff (1967), including England, according to Manley (1959). The summer–winter temperature range was large around 1890 but smallest around 1920. This remarkable decrease in continentality which according to Wagner (1928[b]) began in most of Europe in the late eighteenth century slowly shifted southwards, until in the most pronounced phase (1886–95)–(1911–20) it became concentrated between lat. 35° N. and 60° N., extending from the North Atlantic to Central Asia (Wagner, 1928[a]). The decrease in the summer–winter temperature range was interpreted rightly in Wagner's (1929[b]) famous paper as caused by a world-wide increase in zonal circulation from the decade 1886–95 to the decade 1911–20. At the same time mean annual temperature was found to be increasing on the continents, but decreasing over the sea; the latter changed later on. Wagner's conclusion that the decreasing annual temperature range in Europe since the late eighteenth century was indicative of a generally increasing zonal flow during all of the nineteenth century is fully supported by Lamb and Johnson (1961).

In dealing with glacier variations, Wagner (1929[a]) claimed that the dominating phenomenon since the beginning of the nineteenth century was a general retreat of glaciers interrupted only by minor partial advances, strikingly inversely parallel to the intensity of the general circulation. As precipitation had increased during the second half of the nineteenth century in the vicinity of the Alps, and summers went cooler, increased ablation was assumed to be caused by an increase in the frequency of föhn winds in connexion with the increase in atmospheric circulation. Judging from the results of heat-budget investigations on glaciers of the Alps, this is not likely to be of great influence because increased cloudiness tends to reduce short-wave radiation in compensation of the increased turbulent flux of sensible and latent heat. Besides, frequency of föhn winds has greatly diminished since the decade 1911–20. After having considered Easton's (1928) results that winters in western Europe on an average had been less severe before the year 1600, thus indicating again more vigorous atmospheric circulation before the great advance of glaciers around 1600, Wagner (1940) defined his

* The author is indebted to Dr. H. von Rudloff for readily supplying mean deviations from the 1851 to 1950 average for the period June to August of each year.

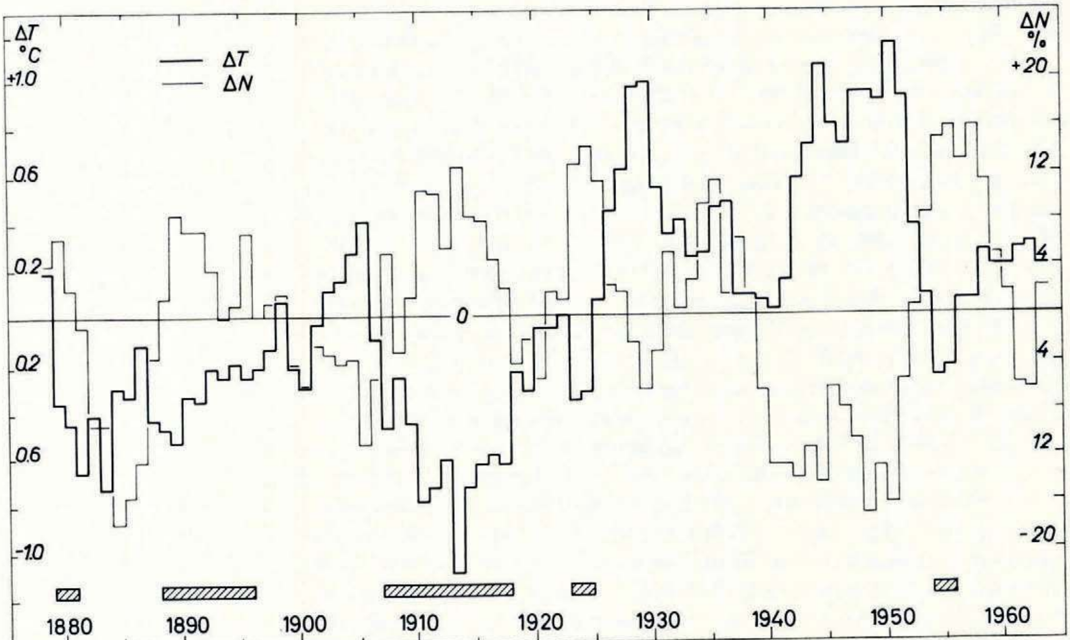

Fig. 2. Five-yearly overlapping mean deviations from the 1851–1950 average of temperature and precipitation in summer (June–July–August) for seven stations above 2 000 m altitude in the Alps, 1877 to 1966

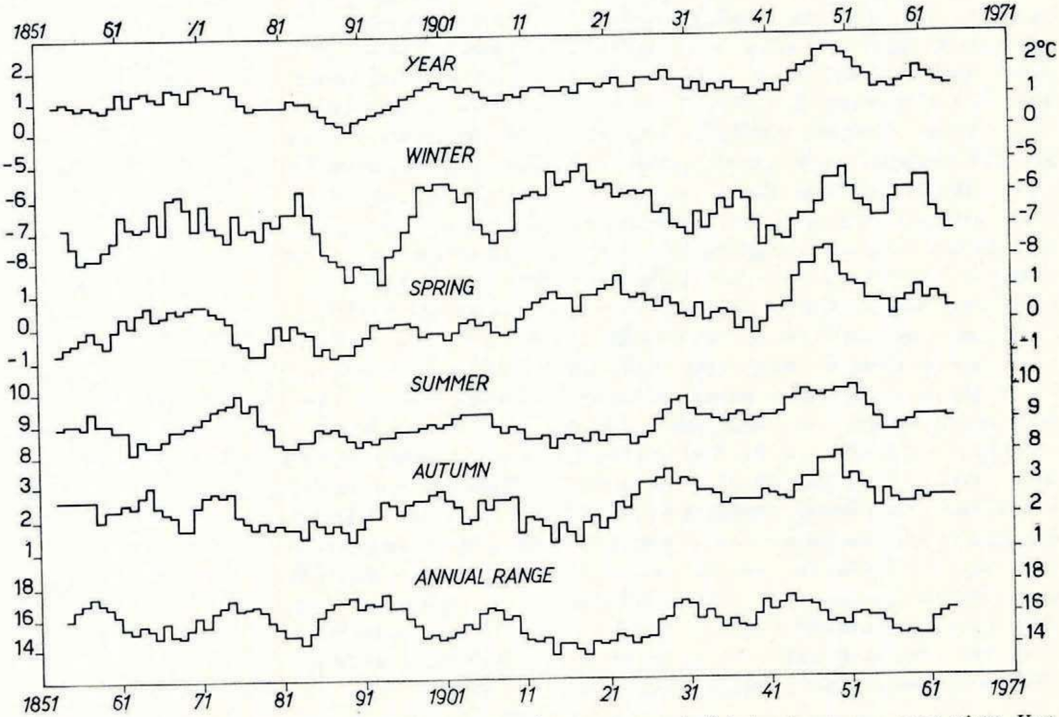

Fig. 3. Five-yearly overlapping means of annual and seasonal temperature, and of temperature range summer–winter, Vent, 1 900 m a.s.l. From Lauffer (unpublished)

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statement as follows:* "According to all records, glaciers in the Alps were in their most advanced positions for some centuries with weak atmospheric circulation, i.e. cold winters and low annual temperature, whereas an increase in atmospheric circulation causes a retreat of glaciers. The speed of glacier flow, which depends on average temperature, seems, therefore, to exert a decisive influence on glacier variations".

Unfortunately this statement has been widely accepted in explanation of glacier variations, and has entered some textbooks, however doubtful it may prove. The following objections to it are suggested:

(1) Glacier variations are not reported unbiased. Strange to say the 1920 advance is barely mentioned by Wagner and considered entirely insignificant although it had been definitely more pronounced than the 1890 advance. Glacier advances around 1850 and around 1820 were as large as or even larger than the advance in the early seventeenth century. Before 1600 glaciers were not entirely insignificant; in about A.D. 1200±70 the advancing Grosser Aletschgletscher had the same size as today and has never been smaller since then (Oeschger and Röthlisberger, 1961). The course of glacier variation and of circulation intensity, therefore, is not obviously inversely parallel, as claimed.

(2) There is no physical reason for temperate glaciers to acquire their largest extent with weak atmospheric circulation producing cold winters, low average temperature and large annual temperature range, i.e. increased continentality. The suggested reduction in velocity of ice flow is insufficient and contrary to the observed increase in velocity during a period of advance. Retreating glaciers are known to have a much reduced velocity which accelerates the mass loss of the lower parts of glaciers. Surge-type advances excluded, the glacier has to accumulate its growing mass before an advance either during a period of several years with heavy solid precipitation in mild winters and/or by preserving normal winter accumulation by reduced ablation in cool and cloudy summers with frequent falls of fresh snow. With respect to glacier variations in the Alps this is well supported by Lamb and Johnson (1961) who report for the period 1200 to 1550 a climatic decline "indicated by an erratic, but on the whole progressive trend towards wetter summers and more frequent severe winters in temperate Europe", and for 1550–1700 "cold or severe winter months and wet Julys and Augusts predominating. The 1590s and 1690s were probably the worst decades". With respect to the atmospheric circulation "this culminating period of the Little Ice Age suggests a shorter wavelength and a generally weaker circulation with the depression tracks and main belt of upper westerlies very appreciably farther south in the European sector than the earlier and later epochs. Wetness of the summers in all longitudes in 50–60° N suggests surface west winds prevailing across the European plain with many depressions passing near 60° N". All this indicates a decisive influence of the character of weather conditions during the ablation season on glacier mass budget, as pointed out by Hoinkes and Rudolph (1962) on the basis of a comparison of mass-budget data and atmospheric conditions for Hintereisferner. The same conclusion had been derived from observations on Kårsa Glaciären much earlier by Wallén (1949).

(3) Wagner's analysis of atmospheric circulation was based on mean annual values of pressure and temperature averaged over a decade. Two decades were compared, 1886–95 and 1911–20. Weak atmospheric circulation is not necessarily equivalent to low annual temperature as around 1890, when extremely low winter temperatures were decisive. Since about 1930 the intensity of atmospheric circulation began to weaken (Scherhag, 1950) with a sharp drop around 1940 (Lamb, 1965). The summer–winter temperature range experienced a decided rise since 1930 (Manley, 1953; Lamb and Johnson, 1961), and yet, mean annual temperature rose to a marked peak in the late 1940's (see Fig. 3). According to Rudloff (1964) by far the warmest decade since 1818 at altitudes above 2 000 m in the Alps was 1942–51. From Table I it becomes manifest that even more than warm summers, extremely warm

* Translated by the present writer.

TABLE I. DEVIATIONS FROM THE 1851–1950 AVERAGE OF MEAN AIR TEMPERATURE AT STATIONS ABOVE 2 000 m ALTITUDE IN THE ALPS (Rudloff, 1964)

Decade	*Spring*	*Summer*	*Autumn*	*Winter*	*Year*	*Summer–winter range*
	deg	deg	deg	deg	deg	deg
1886–95	−0.31	−0.21	+0.07	−1.17	−0.44	+0.96
1911–20	+0.39	−0.66	−0.76	+0.78	−0.04	−1.44
1942–51	+1.27	+0.88	+0.94	−0.06	+0.81	+0.94

spring and autumn temperatures contributed to this most unusual warming. This prolongation of the ablation season was aggravated by a pronounced increase in the duration of bright sunshine. In Vent, according to Lauffer (unpublished), during the ablation season May to September the average duration of bright sunshine rose from 769 h between 1936–40 to 865 h in 1941–50 and to 894 h in the period 1946–50. The highest number of hours with bright sunshine in one ablation period, viz. 979 h, was observed in 1947, the second highest of 944 h in 1950. This increase in the duration of bright sunshine was a general feature in the Alps (Steinhauser, 1957). This period of most severe glacier melt was associated with weak atmospheric circulation. Wege (1961) in comparing air pressure for the periods (1901–30)–(1931–60) found pressure differences indicative of diminishing zonal flow in January, but of increased meridional flow from the south or south-west in July. This is well supported by the frequency of weather types in the British Isles, as reported by Lamb (1965) for the periods 1873–97, 1898–1937 and 1938–61. From the second to the third period there is a sharp decrease in westerly type in the winter months and an increase of southerly type in spring, summer and autumn. It seems, therefore, absolutely necessary to study atmospheric circulation by seasons, and to take into consideration meridional circulation as well, because "resolution of the circulation into zonal and meridional components, and the study of each separately, is clearly capable of bringing different phenomena into prominence" (Lamb and Johnson, 1961).

Even though a clear relationship can be found between glacier variation and deviation from the long-period average of climatic elements, which is reasonable from the viewpoint of heat budget, i.e. a warm summer being more important in the sense of a summer with higher than average solar radiation and with lower albedo of glaciers due to the scarcity of falls of fresh snow, this contributes little to our understanding of the reasons for such deviations. There is a gap to close between the micro-dimension (heat budget) and the macro-dimension (glacier–climate relations) of glacial meteorology. The connecting links are the largely neglected glacier–weather relations in the meso-dimension of glacial meteorology. There must be a close correlation between glacier mass budget and meso-scale weather. The problem is to find, preferably in regularly published data, the right parameter or parameters describing aspects of mesoscale weather, such as are known to characterize heat budget conditions during the ablation season. Emphasis is put on weather conditions during the ablation season because they are considered more important for glacier welfare than weather conditions during the accumulation season, although it is fully realized that "accumulation is the life blood of a glacier" (Sharp, 1960), and that both aspects have to be considered.

As can be seen from Figure 4 there is a good negative correlation of mean specific mass budget of Hintereisferner and of Grosser Aletschgletscher with the deviations from the 1951–60 average height of the 500 mbar surface over München and Payerne (W.M.O., 1965) from May to September, 1953 to 1965. No correlation seems to exist with the vigour of the European north-westerlies, i.e. the pressure difference between the points lat. 50° N., long. 0° E. and lat. 60° N., long. 15° E., which, according to Lamb and Johnson (1961) "is rather closely related to the overall pressure difference between the Azores maximum and the north European minimum". This is somewhat disappointing because it is the only index of circulation intensity which has some resemblance with glacier variations in the Alps, at least in 10-year and 40-year running means for July (see Lamb and Johnson, 1961, figs. 24 and 25).

If this resemblance with glacier variation could be considered a connexion between cause and effect, a close correlation with glacier mass budget should be expected even in the short period available.

The correlation of glacier mass budget with the deviation from the average height of the 500 mbar surface is clearly not restricted to the Alps. As could be shown by Hoinkes [c1964], characteristic deviation patterns from the average height of the 500 mbar surface are associated with diverging glacier mass-budget data in the Alps and in Scandinavia (see Fig. 4, Table II and Fig. 5). Negative mass budget on Storglaciären (Schytt, 1962) and balanced (Hintereisferner) or positive (Grosser Aletschgletscher) mass budget in the Alps in 1959/60 is associated with a low-index situation, developed best from July to September, but characterizing the ablation season May to September 1960 as a whole. Positive mass budget in Scandinavia and

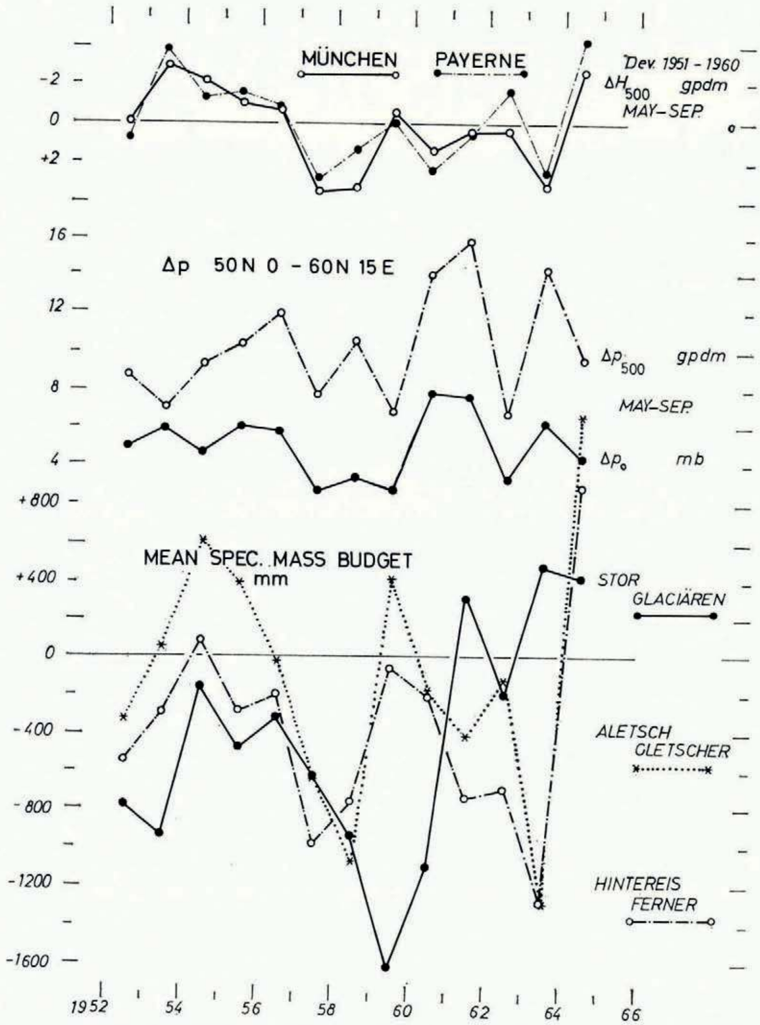

Fig. 4. Mean specific mass budget in mm of water of Grosser Aletschgletscher, Hintereisferner and Storglaciären 1952/53 to 1964/65. Mean pressure difference (surface and 500 mbar) between lat. 50° N., long. 0° E. and lat. 60° N., 15° E. (European north-westerlies), May to September 1953 to 1965. Mean deviation from the 1951–1960 average height of the 500 mbar surface over München and Payerne, May to September 1953 to 1965 in geopotential decametres (gpdm)

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TABLE II. MEAN SPECIFIC MASS BUDGET OF GLACIERS AND CIRCULATION CHARACTERISTICS

Budget year	1959/60	1960/61	1961/62	1962/63	1963/64	1964/65
Grosser Aletschgletscher lat. 46° N., long. 08° E.	+412	−180	−412	−118	−1293	+1257 mm
Hintereisferner lat. 47° N., long. 11° E.	−62	−205	−686	−687	−1245	+925 mm
Kesselwandferner lat. 47° N., long. 11° E.	+118	+271	−416	−406	−537	+1040 mm
Storglaciären lat. 68° N., long. 19° E.	−1610	−1100	+320	−190	+490	+430 mm
Nigardsbreen	—	—	+2250	−220	+950	+910 mm
Storbreen lat. 62° N., long. 07° E.	−1090	−520	+720	−1180	+210	+340 mm
DEVIATION FROM AVERAGE (1951–60) HEIGHT OF 500 mbar SURFACE, MAY TO SEPTEMBER						
München	−0.6	+1.4	−0.9	+0.3	+3.1	−2.7 gpdm*
Payerne	0.0	+2.4	+0.6	−1.6	+2.5	−4.3 gpdm
AVERAGE PRESSURE DIFFERENCE LAT. 50° N., LONG. 0° E. TO LAT. 60° N., LONG. 15° E., MAY TO SEPTEMBER						
Surface	2.7	7.8	7.7	3.2	6.2	4.3 mbar
500 mbar	6.8	13.9	15.8	6.7	14.3	9.6 gpdm

* geopotential decametres.

negative mass budget in the Alps in 1961/62 on the other hand, is associated with a high-index situation, again lasting through the ablation period. In the budget year 1963/64, glaciers in the Alps were on their most negative mass budget since 1952/53, and Storglaciären experienced again a positive mass budget (Schytt, 1965). The deviation pattern of the height of the 500 mbar surface is very similar to the one of the ablation season of 1962, indicating again a high-index situation in the European sector (see Fig. 5). In the budget year 1964/65 positive mass budget persisted on Storglaciären, leading to an increase in thickness along its whole length (Schytt, 1966). At the same time the mass budget of Hintereisferner and of Grosser Aletschgletscher became positive. Positive mass budget was found on all glaciers under observation in the Alps and in Scandinavia as reported in *Ice*, No. 20 (April 1966) and No. 22 (December 1966). In Table II of the results of mass budget investigations carried out in Norway only data of Nigardsbreen and of Storbreen are included (Østrem and Karlén, 1963; Østrem and Liestøl, 1964; Pytte and Østrem, 1965; Pytte and Liestøl, 1966). During the ablation season May to September 1965 negative deviations from the average height of the 500 mbar surface prevailed both in Scandinavia and in the Alps. The average deviation pattern again indicates a high-index situation in the European sector (Fig. 5).

It seems remarkable that pronounced deviation patterns from the average height of the 500 mbar surface in the European sector are associated with equally pronounced variations of glacier mass budget in the Alps and in Scandinavia, even though only the ablation season May to September is considered. It is worth mentioning that in all four ablation seasons shown in Figure 5, i.e. 1960, 1962, 1964 and 1965, an equally clear picture could not have been obtained by taking for instance the pressure difference between the Azores and Iceland or any other two points in the North Atlantic as a measure of the circulation intensity affecting glaciers in Europe. For this purpose a meridional deviation profile through mid-Europe, e.g. along long. 10° E., or even better the mean deviation profile along longs. 0° E., 10° E. and 20° E., is more appropriate. Figure 6 contains such profiles for all months of the ablation seasons 1960, 1962, 1964 and 1965. With very few exceptions the character of average atmospheric circulation, as shown in Figure 5, prevails in every month of the respective ablation season making the deviation patterns meaningful. Mass budget of glaciers in the Alps may be found positive or balanced with a low-index circulation lasting through the ablation season, as in 1960, or with a high-index circulation as in 1965 (with the exception of

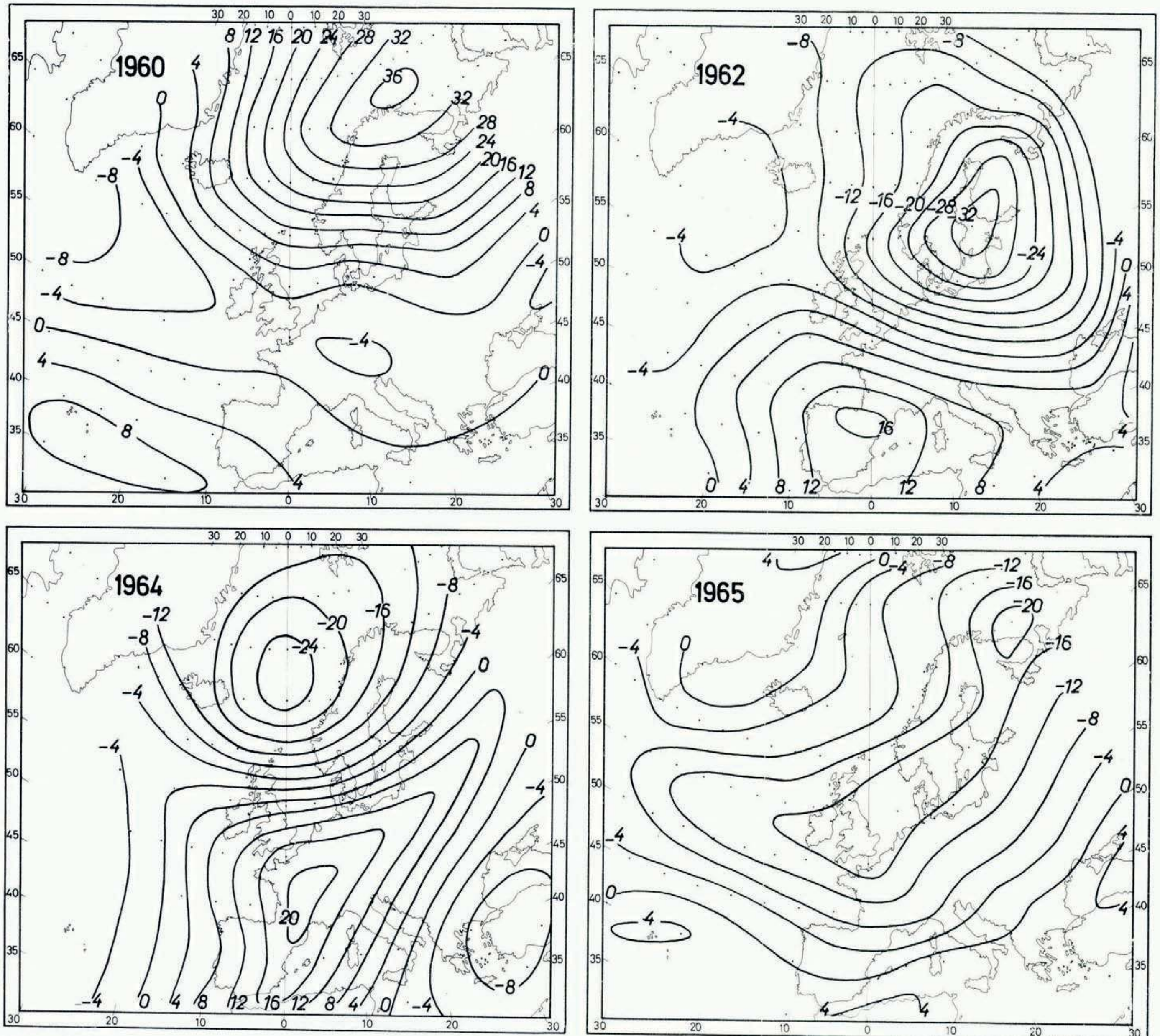

Fig. 5. Deviation from the average height of the 500 mbar surface (1949–58 for 1960 and 1962, 1949–63 for 1964 and 1965), ablation season May to September 1960, 1962, 1964 and 1965, in gpdm compiled from Grosswetterlagen Mitteleuropas, *published by Deutscher Wetterdienst, Zentralamt Offenbach*

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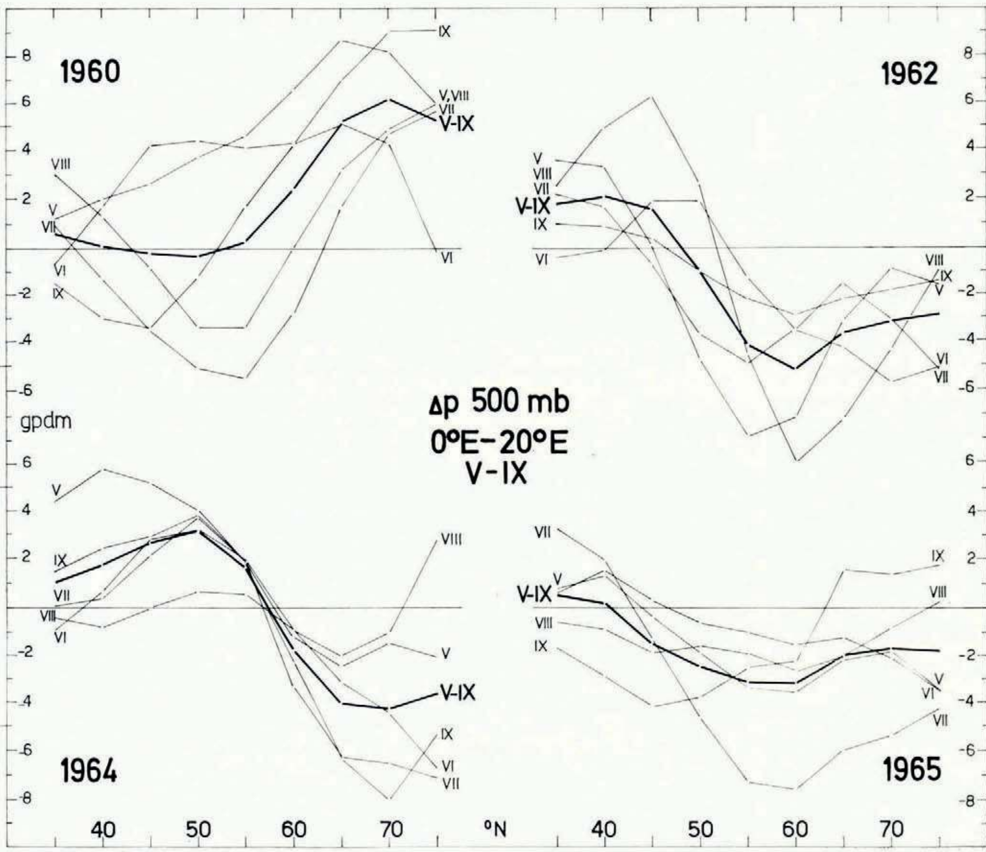

Fig. 6. Mean meridional deviation profiles from the average height of the 500 mbar surface through mid-Europe long. 0° E. to long. 20° E., ablation season May to September 1960, 1962, 1964 and 1965

September). On the other hand other high-index summers as, e.g. 1962 or 1964, were associated with negative mass budgets in the Alps, depending on the latitude of zero deviation. More important than the circulation type seems, therefore, the sign of the deviation from the average 500 mbar surface in the area under consideration as an indication of predominant cyclonic or anticyclonic conditions during the ablation season. The mean deviation for the area "Alps" was calculated from nine points of intersection between longs. 0° E., 10° E. and 20° E., and lats. 40° N., 45° N. and 50° N., that for the area "Scandinavia" for the same degrees of longitude, and lats. 60° N., 65° N. and 70° N. (see Table III).

TABLE III. SUM OF DEVIATIONS FROM THE AVERAGE HEIGHT OF THE 500 mbar SURFACE, ABLATION SEASON MAY TO SEPTEMBER

"Alps" means average between longs. 0° E. and 20° E., lats. 40° N. to 50° N.
"Scandinavia" means average between the same degrees longitude, lats. 60° N. to 70° N.

Year	1960	1962	1964	1965	
Alps	−0.6	+4.6	+12.4	−6.4 gpdm	(geopotential decametres)
Scandinavia	+23.1	−20.1	−16.9	−11.4 gpdm	

Defined deviation patterns from the average height of the 500 mbar surface should be related to the frequency of certain *Grosswetterlagen*, that is to say "fairly persistent synoptic situations which determine the form and sequence of weather events for a period of several days or even weeks" (Trewartha, 1962). The frequency of *Grosswetterlagen* or of certain groups thereof could well form the connecting link between climate and micrometeorology. Hess and Brezowsky (1952) have published a catalogue of the *Grosswetterlagen* of mid-Europe for each day of the period 1881 to 1950, containing also examples for the 28 different *Grosswetterlagen* used. Since 1951 this classification has been continued in the publication *Grosswetterlagen Mitteleuropas*, issued monthly by Deutscher Wetterdienst, Zentralamt Offenbach. It was convenient to use some of the groups of *Grosswetterlagen* introduced and studied by Bürger (1958) for the period 1890 to 1950.* The frequency of the following groups of *Grosswetterlagen* was studied: W1 oceanic type weather in winter was considered favourable for glaciers even though only a weak positive correlation coefficient of 0.374 ± 0.067 was found between W1 and winter precipitation in Innsbruck, but this might be more significant elsewhere. F4 cold spells in spring are clearly favourable for glaciers, either because of solid precipitation or because of a late beginning of the ablation season, or both. S5 anticyclonic weather in summer is clearly unfavourable for glaciers because of high radiation and temperature and low albedo. S6 monsoon-type weather in summer is the most important group of favourable *Grosswetterlagen* for glaciers because of reduced radiation and increased albedo caused by frequent falls of fresh snow. Of the group of *Grosswetterlagen* responsible for fine weather in autumn only September (s7) was considered because ablation only rarely continues through October. As can be seen from Table IV, *Grosswetterlagen* representing zonal, meridional and mixed-type circulation forms are brought together in each group.

Figure 7 contains the frequency in days of the respective groups of *Grosswetterlagen* for every season since the winter of 1880/81 until September of 1966. The heavy line represents five-yearly overlapping means (1881 to 1885 entered on 1883, 1962 to 1966 entered on 1964). The course of the frequency of W1 resembles to a high degree the course of winter precipitation in western Austria (Steinhauser, 1963). Glacier advance around 1890 occurred with very few *Grosswetterlagen* of the type W1 and also with very low winter precipitation (below 80 per cent of average 1891–1950, five-yearly minimum 63 per cent in 1889). Glacier advance around 1920 was definitely supported by increasing winter precipitation (up to 120 per cent of average 1891–1950, five-yearly maximum 129 per cent in 1921), but highest winter precipitation around 1950 (up to 130 per cent of average 1891–1950, five-yearly maximum 133 per cent in 1946) could however not stop glacier retreat caused by sunny and dry summers together with a prolonged ablation season. This is clearly indicated by a minimum of cold spells in spring (F4) in the mid-forties, with a five-yearly minimum of spring precipitation in western Austria of 80 per cent in 1948. The course of the frequency of *Grosswetterlagen* S6, i.e. monsoon-type weather in summer, shows rising values to a maximum of 1894, and again high values from 1906 to 1910. The striking decrease of S6 after 1930 is most remarkable. Between 1881 and 1930 there were 14 summers with 65 or more days of this type, after 1930 this number was reached only once. A five-yearly average of 58 or more days of S6 occurred 17 times between 1883 and 1932, but no more since. The lowest five-yearly average before 1930 was 49 days of S6 with three occurrences, after 1930 19 five-yearly averages were lower than 49 days. The variation in the frequency of anticyclonic type weather in summer S5 runs complementary to S6 with minima from 1890 to 1894 and from 1906 to 1910 and rising from 1930 onwards. There were only two summers with 48 or more days of anticyclonic *Grosswetterlagen* before 1930, but six after 1930 with the highest number of 65 days in 1947. A five-yearly average of 38 days of S5 occurred twice before 1930 but nine times after 1930. The five-year period with the maximum average number of anticyclonic *Grosswetterlagen*, viz. 45 days in 1946–50 also had the highest duration of bright sunshine during the ablation season in Vent. Twelve summers before 1930 had 20 days or less of anticyclonic *Grosswetterlagen* but there was only one such summer after 1930. The lowest five-yearly average of S5 after 1930

* The author is indebted to Dr. H. Brezowsky for supplying the necessary data to close the gaps left in the above-mentioned catalogue in the spring of 1945.

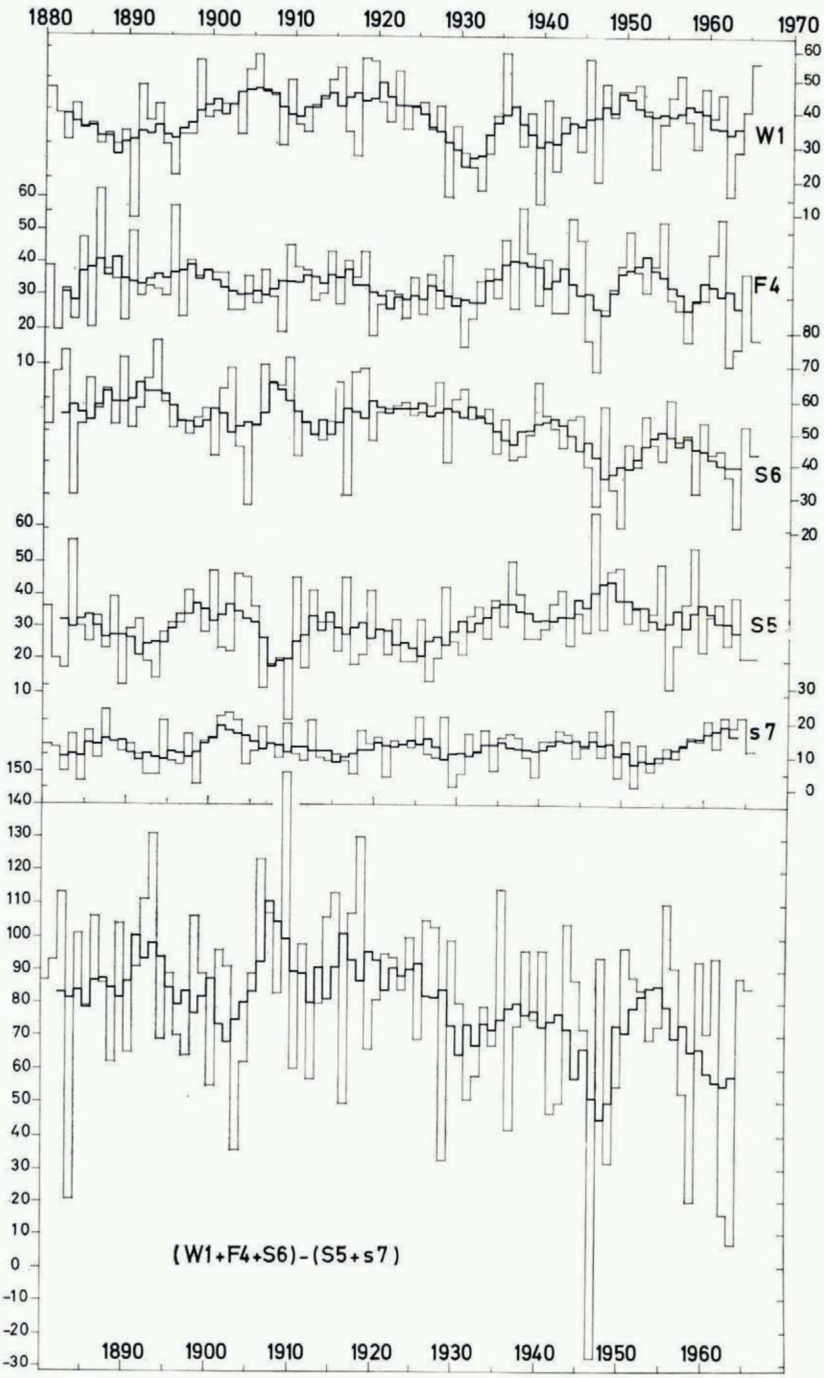

Fig. 7. Frequency of groups of Grosswetterlagen *in days according to Table IV, 1881–1966. Heavy line: five-yearly overlapping means*

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TABLE IV. GROUPS OF *Grosswetterlagen* (Bürger, 1958)

Group	*Description*	*Circulation*	*Grosswetterlagen* (Hess and Brezowsky, 1952)							
W1	oceanic type weather in winter	zonal	Wa	Wz	Ws					
		mixed	NWa	NWz	SWz					
		meridional	Ww	TB	TrW					
F4	cold spells in spring	zonal	—							
		mixed	NWa	NWz						
		meridional	Na	Nz	HNa	HNz	HB	TrM	NE	
S6	monsoon type weather in summer	zonal	Wz	Ws						
		mixed	NWa	NWz						
		meridional	Na	Nz	HNa	HNz	HB	TrM	TM	
S5	anticyclonic weather in summer	zonal	Wa	BM						
		mixed	SWa	HM						
		meridional	Sa	SEa	HFa	HNFa	NE			
s7	fine weather in September	zonal	BM							
		mixed	SWa	HM						
		meridional	Sa	Sz	SEa	SEz	TB	TrW	HFa	HNFa

Explanation of symbols:

(i) zonal circulation
- Wa westerly type, anticyclonic
- Wz westerly type, cyclonic
- Ws westerly type, over the southern part of Central Europe
- BM bridge of high pressure over Central Europe

(ii) mixed circulation
- NWa northwesterly type, anticyclonic
- NWz northwesterly type, cyclonic
- SWa southwesterly type, anticyclonic
- SWz southwesterly type, cyclonic
- HM closed anticyclone over Central Europe

(iii) meridional circulation
- Ww westerly type, changing to southerly type over the eastern part of Central Europe
- TB closed cyclone over the British Isles
- TM closed cyclone over Central Europe
- TrW trough over Western Europe
- TrM trough over Central Europe
- HB closed anticyclone over the British Isles
- Na northerly type, anticyclonic
- Nz northerly type, cyclonic
- NE northeasterly type
- Sa southerly type, anticylonic
- Sz southerly type, cyclonic
- SEa southeasterly type, anticyclonic
- SEz southeasterly type, cyclonic
- HNa closed anticylone over the North Atlantic Ocean, anticylonic weather over Central Europe
- HNz closed anticylone over the North Atlantic Ocean, cyclonic weather over Central Europe
- HFa closed anticylone over Fennoscandia, anticyclonic weather in Central Europe
- HNFa closed anticylone over the North Atlantic Ocean and over Fennoscandia, anticyclonic weather in Central Europe

was 29 days with three occurrences, between 1883 and 1930 there were 25 five-yearly averages with 29 days of S5 or less.

This truly remarkable increase of anticyclonic *Grosswetterlagen* in summer with high insolation and high temperature aloft, and at the same time the decrease of cyclonic *Grosswetterlagen*, as an indication of decreasing occurrences of fresh snow in summer and consequently decreased average albedo of glaciers (Hoinkes, 1955; Fliri, 1964) is clearly related to the glacier recession of the last four decades. According to Finsterwalder (1953) the change in volume of eight glaciers in the Eastern Alps between 1920 and 1950 was equivalent to an average specific mass loss of 550 mm of water per year. The same order of magnitude was reported for the period 1926 to 1957 for Grosser Aletschgletscher by Kasser (1961). The five-yearly average number of days with *Grosswetterlagen* favourable for glaciers (W1+F4+S6) shows a peak of 140 d between 1886 and 1890, and two adjacent peaks of 142 d between

1906 and 1910, and of 139 d between 1915 and 1919. The highest numbers for single years were 169 d in 1919, and 167 d in 1911. The average number of 136 d for 1919–23 was the last five-yearly average above 130. There was a secondary maximum of 127 d in the period 1951 and 1955, between two critically low minima of 102 d and 104 d for 1946–50 and 1962–66 respectively. The lowest five-yearly average before 1930 had been 112 d in 1882–86, the next lowest value being 123 d in 1901–05; after 1930 there were 12 five-yearly averages below 112 d. The lowest numbers for single years were 55 d in 1947, followed by 62 d and 65 d in 1963 and 1964 respectively. The five-yearly average number of days with *Grosswetterlagen* unfavourable for glaciers (S5+s7) shows the lowest value of 31 d in the period 1890–94, and again with 31 d in the period 1906–10. The lowest numbers for single years were 17 d in 1910, and 19 d in 1894. The pronounced maximum of 55 d in 1901–05 was exceeded by the highest five-yearly average of 58 d in 1947–51. Of the 11 five-yearly averages of more than 50 d of unfavourable *Grosswetterlagen* in one ablation season three occurred before 1930 (1900–04, 1901–05, 1902–06), and eight after 1930. The highest numbers for single years were 82 d in 1947, 73 d in 1884 and 71 d in 1949.

Assuming that one day with an unfavourable *Grosswetterlage* compensates for one day with a favourable one, the difference of the frequencies (W1+F4+S6)−(S5+s7) should yield a curve (see lower part of Fig. 7) which resembles the statistical result of observed variations of glaciers. A comparison with Figure 1 shows this to be the case to an astonishingly high degree. The period of glacier advance around 1890 corresponds in the five-yearly overlapping means of excess days with favourable *Grosswetterlagen* to increasing values from 1885–90 reaching a peak of 100 favourable days in 1890 to 1894. Unfortunately the number of glaciers under regular observation was rather low at that time (Fig. 1). The following period of heavy glacier melt is interrupted by a short tendency towards advance in 1902/03, caused by a rising number of remaining favourable *Grosswetterlagen* to a five-yearly average of over 87 in 1899 to 1903. The sharp decrease to only 36 favourable days in 1904, leading to a low five-yearly average value of 68 days in 1901–05 corresponds to a minimum number of advancing glaciers in 1904. The glacier advance culminating around 1920 begins to prepare itself with a sharp rise of the number of favourable *Grosswetterlagen* from 1906 on. The first peak with 110 d is reached in 1906–10 with the highest number of 150 d in a single year (1910); then the values stay relatively high to reach a second five-yearly peak of 101 d in 1915–19. The last high value of 92 d in 1924–28 corresponds to the 50 per cent advancing glaciers in 1926 (see Fig. 1). The long period of glacier recession to the minimum of 1947 corresponds to decreasing frequencies, down to the lowest five-yearly average of remaining favourable *Grosswetterlagen* of only 45 d in 1946–50. In 1947 there was an excess of 27 d with unfavourable *Grosswetterlagen* (55 d classified favourable between December and August, i.e. out of 274 d, versus 82 d classified unfavourable between June and September, i.e. out of 122 d). The temporary tendency to glacier advance in the mid-fifties has an equivalent rise to an average of 85 d in 1953–57. The most recent tendency to glacier advance in the Alps as indicated by positive mass budgets in 1965 and 1966 does not yet show in the five-yearly overlapping means of favourable *Grosswetterlagen* because of the extremely low numbers of 16 and 7 such days in 1963 and 1964, respectively, corresponding to very negative mass-budget values (Table II). Nevertheless, it looks as if the five-yearly average of 55 days in 1961–65 would remain a minimum.

A five-yearly mean number of at least 90 d with favourable *Grosswetterlagen* in excess of days with unfavourable *Grosswetterlagen* (in the present definition) seems to be a condition necessary for a glacier advance in the Alps. The longer this condition lasts, the more glaciers will become advancing. In the case of the 1920 advance, the first five-yearly average to fulfil this condition was 1905–09, and the last 1924–28. Of the 20 five-yearly overlapping means, 13 were over 90 d, 17 over 85 d, and all of them over 80 d, giving a mean value of 93 d with excess of favourable *Grosswetterlagen* per year for the period 1907–26. Table V

Table V. Maximum, Minimum and Average Numbers (Days) of Groups of *Grosswetterlagen* for Consecutive Periods of Five, Ten, Twenty and Forty Years, 1881–1965

	$(m4+S6)-(S5+s7)$								$(W1+F4+S6)-(S5+s7)$							
	maximum d/year		*minimum d/year*		*5-year*	*10-year averages*	*20-year*	*40-year*	*maximum d/year*		*minimum d/year*		*5-year*	*10-year averages*	*20-year*	*40-year*
1881–85	66	(83)	−36	(84)	24.4				113	(83)	21	(84)	83.0			
					(22.4)											
1886–90	57	(90)	6	(89)	34.2				106	(87)	62	(89)	87.4			
					(34.6)	35.3								90.4		
1891–95	72	(94)	15	(95)	36.4	(35.6)			131	(94)	69	(95)	93.4			
					(36.6)		26.6								83.1	
1896–00	39	(96)	7	(98)	25.8		(25.2)		106	(99)	64	(98)	83.6			
					(18.2)	17.9								75.8		
1901–05	41	(02)	−17	(04)	10.0	(14.9)			96	(02)	36	(04)	68.0			
					(11.6)			27.3								88.4
1906–10	75	(10)	10	(06)	44.4			(27.4)	150	(10)	83	(09)	110.4			
					(46.2)	31.7								95.3		
1911–15	35	(12)	2	(13)	19.0	(30.5)			106	(15)	57	(13)	80.2			
					(14.8)		28.0								93.6	
1916–20	53	(18)	−17	(17)	22.4		(29.6)		130	(19)	50	(17)	93.2			
					(25.4)	24.4								92.0		
1921–25	36	(22)	18	(21)	26.4	(28.7)			100	(25)	81	(21)	90.8			
					(32.0)											
1926–30	52	(28)	−14	(29)	28.8				105	(27)	33	(29)	81.8			
					(32.4)	25.8								74.4		
1931–35	40	(31)	7	(32)	22.8	(27.5)			80	(31)	51	(32)	67.0			
					(22.6)		21.6								76.4	
1936–40	45	(40)	−21	(37)	16.6		(22.0)		114	(36)	42	(37)	80.0			
					(14.8)	17.4								78.4		
1941–45	30	(44)	1	(43)	18.2	(16.4)			104	(44)	47	(42)	76.8			
					(18.0)			13.7								70.2
1946–50	30	(48)	−48	(47)	−10.8			(14.1)	94	(48)	−27	(47)	45.2			
					(−8.8)	3.3								63.7		
1951–55	26	(53)	5	(55)	17.4	(−0.1)			97	(51)	69	(54)	82.2			
					(8.6)		5.8								64.0	
1956–60	43	(56)	−17	(59)	15.8		(6.2)		110	(56)	20	(59)	73.4			
					(17.4)	8.3								64.3		
1961–65	23	(65)	−34	(64)	0.8	(12.5)			94	(62)	7	(64)	55.2			
					(7.6)											

* average values in brackets are (S6−S5).

contains the highest, lowest and average numbers of groups of *Grosswetterlagen* according to Table IV for consecutive periods of five, ten, twenty and forty years, 1881 to 1965. If only the ablation period May to September is considered, one obtains a very similar distribution, and this even remains the case when only the difference (S6−S5) is taken into account; these average values are given in brackets in Table V. The decreasing differences clearly demonstrate how much the character of summer weather has changed since 1930. With the exception of the period 1901–05, cyclonic situations on the average showed an excess of 30 days over anticyclonic situations in the summers of 1886 to 1930; since then this excess has dropped to an average of 11 d, and in 1946–50 anticyclonic situations in summer actually exceeded cyclonic situations by 9 d. Naturally the additional consideration of the frequencies of W1 and F4 as an indication of precipitation in winter and in spring yields a better result. Judging solely from the weather conditions during the ablation season, the 1890 advance should have been better developed, but low precipitation in winter and spring (Steinhauser, 1963) kept it small. The strong influence of increased winter precipitation from 1906 to 1920 in the 1920 advance has already been mentioned; a similarly sharp decrease of winter precipitation from 1920 to 1930 makes it easier to understand the termination of the 1920 advance period, in spite of rather favourable weather conditions in summer lasting until 1928. There was, however, a pronounced increase in the duration of bright sunshine in summer in the Austrian Alps after 1925, culminating in the highest five-yearly average 1927–31 or 1928–32 (Steinhauser, 1957). The glacier recession after 1940 would certainly have been much more devastating without the remarkable increase in winter precipitation observed in the Alps between 1940 and 1950. In Table VI the numbers of days classified in groups of *Grosswetterlagen* are given for the single budget years 1959/60 to 1964/65, for which mass budget data were shown in Table II. It will be noted that a fairly good agreement between the pattern of mass budget of alpine glaciers and the pattern of the difference of favourable and unfavourable *Grosswetterlagen* exists. This is better for summer (S6 − S5) or for the ablation season May to September (m4 + S6) − (S5 + s7) than for the period December to September. In this case the year 1961/62 does not fit; most probably some of the *Grosswetterlagen* classified in groups W1 or F4 did not have the expected effect. In general, the qualitative agreement is satisfactory.

TABLE VI. NUMBER OF DAYS CLASSIFIED IN GROUPS OF *Grosswetterlagen* FOR SINGLE BUDGET YEARS 1959/60 TO 1964/65

		1959/60	1960/61	1961/62	1962/63	1963/64	1964/65
Winter	W1	48	39	46	16	29	41
Spring	F4	29	43	54	10	15	37
May	m4	11	23	16	3	3	13
Summer	S6	53	43	44	36	21	52
Summer	S5	23	34	38	25	40	21
September	s7	14	20	12	21	18	21
(W1 + F4 + S6) − (S5 + s7)		93	71	94	16	7	88
(m4 + S6) − (S5 + s7)		27	12	10	−7	−34	23
(S6 − S5)		30	9	6	11	−19	31

This is but a first and rudimentary trial of a *Grosswetterlagen* climatology related to glaciers and a more detailed investigation is necessary in order to find the best combination of *Grosswetterlagen*. As a method of approach, even though still descriptive, it looks more promising than the classical approach based chiefly on monthly, seasonal or annual averages of temperature and precipitation. The introduction of atmospheric circulation by frequencies of *Grosswetterlagen* contributes to a better understanding of the causes of climatic variations. The close connexion between meso-scale weather and mass budget of glaciers is clearly demonstrated by the fact that a statistics of selected groups of *Grosswetterlagen* resembles so well the statistical evaluation of observed variations in the length of glaciers (Fig. 7), and also the variations in mass budget (Table VI). The cause and effect relation between *Grosswetterlagen* and climatic elements is still very complex, and it is by no means easy to explain all the details of deviations from average summer temperature and precipitation (Fig. 2) in terms of the difference (S6 − S5). This is not surprising if it is realized how very different is the influence of certain *Grosswetterlagen* on climatic elements in different parts of the Alps (Fliri, 1962). The present writer is fully aware of many shortcomings in his dealing with *Grosswetterlagen*. It is an unjustified oversimplification to attach equal weight to all *Grosswetterlagen*, and some *Grosswetterlagen* become even more efficient as the ablation season goes on, due to the lowering of average albedo of glaciers in the course of the ablation period. It is probable that a statistical treatment of weather types would give better results if it was based on a system of classification which takes into consideration the peculiarities of Alpine weather. Neither the system developed by Lauscher (1954) for the eastern Alps, nor the one developed by Schüepp (1959, 1965) were used, simply because the classification of Hess and Brezowsky (1952) was the only one available back to 1881.

It will be noted that the statistics of the difference of groups of *Grosswetterlagen* characterized as favourable and unfavourable for glaciers (W1 + F4 + S6) − (S5 + s7) very fortunately does not reveal the large differences which undoubtedly existed in the intensity of zonal circulation between the decades 1886–95 (90 d) and 1911–20 (87 d). However, according to Lamb (1965), this difference becomes pronounced in the expected sense if the westerly weather type in the British Isles is alone considered. As could be shown by Brezowsky (1952) from the statistics of *Grosswetterlagen* divided into zonal and meridional flow separated by seasons, in winter there was a minimum of zonal flow around 1890 and a maximum between 1905 and 1930. In summer on the contrary there was a well developed zonal flow around 1890, but a maximum of meridional flow from the north to the east from 1905 to 1920. The increase in the intensity of zonal flow from 1886–95 to 1911–20 was obviously most pronounced in winter, and not to the same degree a feature of the whole year. There is definitely no simple relation between the intensity of atmospheric circulation in the sense of zonal circulation, if this is deduced from mean annual data, and glacier variation. In the present attempt therefore, use has been made of zonal, meridional and mixed-type circulation forms. The main result emerging is that since about 1930 weather conditions mainly in the ablation season have become much less cyclonic. This is not only the case in mid-Europe and in the Alps. By comparing the periods 1900–19 and 1920–39, Petterssen (1949) has found a decrease of cyclonic activity over all of Europe. This apparently has continued since, although a detailed study has not become known to the present author. Perhaps the frequency of föhn winds as recorded in Innsbruck could serve as an indication of cyclonic activity. From an average 83 d/year in 1911–20 this frequency has dropped to an average 48 d/year in 1940–65. Seven years between 1906 and 1935 had more than 90 d with föhn (maximum 104 d in 1916) since then the highest value has been only 71 d. Until 1935 not a single year had less than 40 d with föhn, since then there were four such years, the minimum being 21 d in 1955.

It remains to be seen whether or not the present tendency towards positive mass budgets will lead to a new period of glacier advance. But it must be remembered that the result of a period of advance cannot be judged solely by looking at the deviations of climatic elements. It depends also on the size of glaciers at the beginning of such a period and how far from equilibrium size they are (Billwiller, [1950]). That is to say, even if within the next few years deviations of climatic elements and frequencies of favourable *Grosswetterlagen* should become similar to the ones of the period 1906–25, glaciers could hardly be expected to reach the size they had in 1925 within 20 years because of the heavy mass loss suffered during the last 40 years. More important than the absolute value seems to be the duration of deviations of climatic elements from the normal average when dealing with glacier–climate relations.

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