Front variations of outlet glaciers from Jostedalsbreen, western Norway, during the twentieth century

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The record of glacier-front position changes at 15 individual outlet glaciers from Jostedalsbreen during the twentieth century is presented and interpreted. A specific pattern of glacier-front oscillations is recognised, with two readvances during the first part of the century, followed by a strong retreat in the middle of the century turning into the present strong advance. Differences in behaviour of individual outlets depending on specific response times permit their classification into three groups.
In interpreting the interaction glacier-front variations/climatic fluctuations, no dominating factor can be traced. The importance of individual meteorological factors has been changing throughout the century. High winter precipitation and low summer temperatures caused the two readvances of the first part of the twentieth century. The retreat in the middle of the century was mainly the result of high summer temperatures. The present advance is primarily the result of large winter snow accumulations. Although mass balance data are far more suitable for the characterisation of the relationship between climate and glaciers, the record of glacier-front position changes presented here also contains valuable information.

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Introduction

Glaciers are sensitive indicators of climatic fluctuations, today as in the past. Although the climatic significance is reduced by several glaciological factors as well as factors of the natural environment influencing glacier-front oscillations in addition to the influence of the climatic system, glacier-front variations are favourite topics of study. The fronts of the glaciers are easily accessible and measurement records are available for almost all glacier regions over time periods of up to 100 years and more. Therefore, climatic fluctuations are far more often viewed in relation to measured glacier-front variations than to mass balance measurements. Although mass balance data would be preferable for the analysis, with fewer precautions being required, there are unfortunately too few data series available.

Glacier-front oscillations of the recent advance of the outlet glaciers of Jostedalsbreen are very remarkable as they contrast with glaciers in other regions such as the European Alps. At Jostedalsbreen, the first annual measurements of glacier-front position change were made around 1900 at up to 15 individual outlet glacier tongues (see Fig. 1). Unfortunately, measurements stopped around the middle of the twentieth century at a large number of glacier sites. Only at four glaciers (Brigsdalsbreen, Fåbergstølsbreen, Nigardsbreen (not annually but only over a short period) and Stegholtbreen) are there continuous records of glacier-front measurements up to today (measurements have been carried out at Austerdalsbreen as well, but because of a break in observations during the 1920's, a complete record is lacking).

Although the continuous records of Brigsdalsbreen, Fåbergstølsbreen and Stegholtbreen and their response to climatic fluctuations have already been studied (Nesje 1989) and as an overview of the glacier-front variations during the first half of the twentieth century has already been given by Fægri (1948), a detailed presentation of all available records of the Jostedalsbreen outlets has not been published. Even though most of the glacier-front variation records only apply to the first half of the twentieth century, some important inferences on glacial dynamics and glacier-front oscillation chronology can be made by comparing the data of the outlet glaciers in terms of their differences in size, morphology and aspect. This paper presents the record of glacier-front variations of all the Jostedalsbreen outlets measured during all or parts of the twentieth century, depending on the available information (Winkler 1994). By using meteorological data from stations around Jostedalsbreen available for the period of glacier-front observations, the relationship between glacier-front oscillations and climatic fluctuations has been analysed. In addition, the influence of different aspects of climate can be determined by referring to mass balance studies at Nigardsbreen which were begun in 1961/62 (see Østrem et al. 1991).

Glacier-front measurements

Around 1900, Rekstad (1901) began his research at the outlet glaciers of Jostedalsbreen and established a series of marks for the subsequent measurement of changes in the positions of their snouts. Initially, measurements were carried out annually at only a few of the glaciers. Unfortunately, an advance occurred during this period

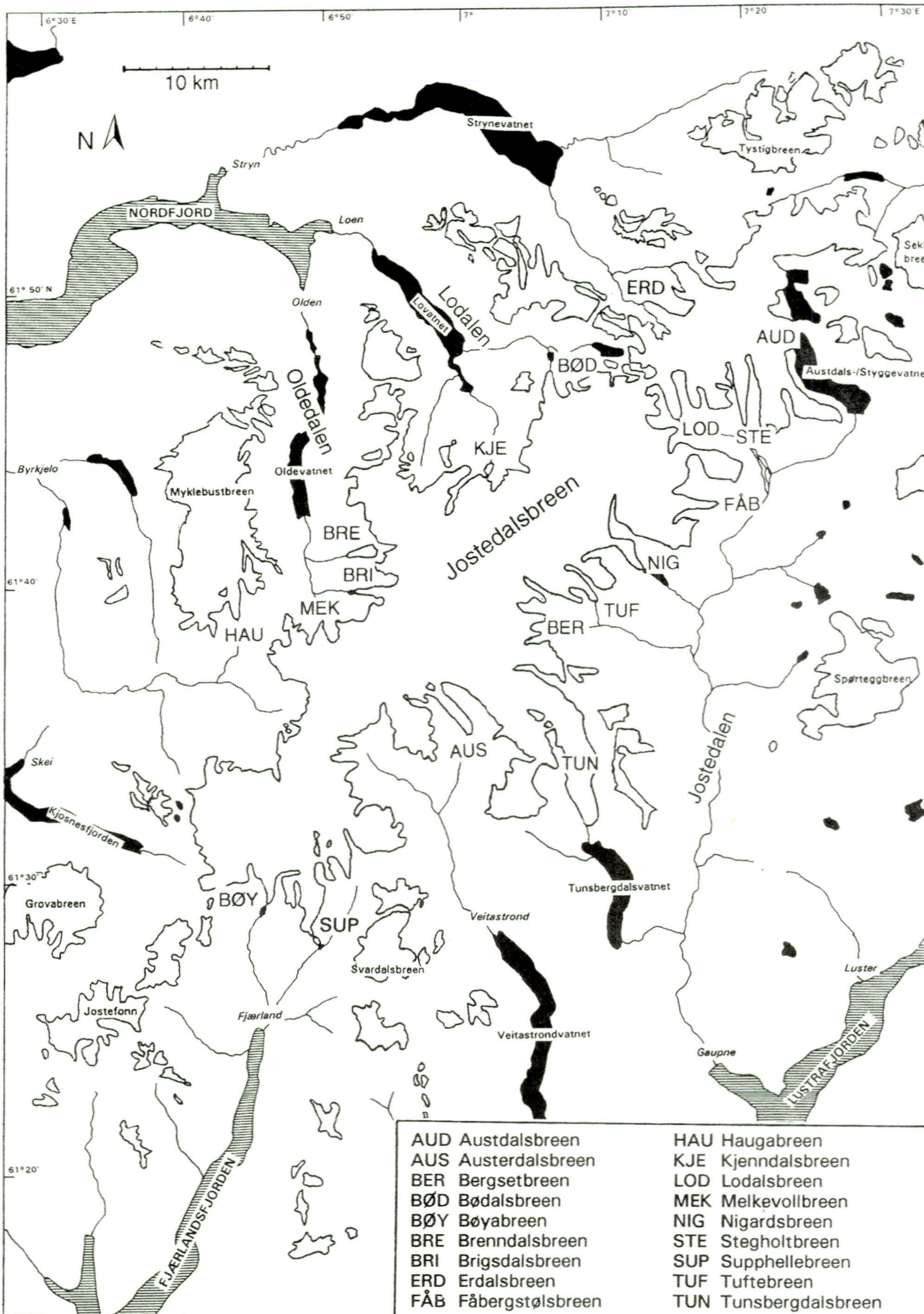

Fig. 1. Sketch map of Jostedalsbreen.

and as a result neither the exact starting points nor the exact advance distances are known for a number of glaciers (see below). However, even though these measurements were not made annually at all 15 outlet glaciers, small retreat or advance distances can be interpreted as a consequence of two or three years of retreat followed by a few years of advance, resulting in a small overall positional change over the whole period.

Annual observations were made during late summer mostly by local people. The compiled results of the measured position changes were reported annually by Rekstad (1910) in the *Bergens Museums Årbok*, complemented by remarks on important events (dramatic changes of glacier morphology, appearance of proglacial lakes, difficulties during measurement procedure, etc.). However, frequent field checks by Rekstad himself, as numerous photographs from the first decade of the twentieth century show (Fotoarkiv, NGU Trondheim), give us an idea about the accuracy attained in the reports of Rekstad and later of Fægri (1934b). The results of the measurements are usually specified for single marks which makes it possible to distinguish between the different sections of a glacier tongue that might have undergone appreciable changes in morphology (e.g. during periods of strong retreat or advance). Unfortunately, those annual measurements stopped after 1941 at the majority of the Jostedalsbreen outlets. Apart from the five glaciers at which measurements are still taken today, the changes in glacier-front position of the other glaciers can only be determined by using ground and air photographs in addition to maps, to compare them with the recent position of the glacier tongues observed during fieldwork (Winkler 1994).

As the annual measurements of the glacier-front position change have been published (Rekstad 1901, Fægri 1934b, Liestøl 1963) and were thus accessible to the present author, it was possible to reconstruct the glacier-front variations for all 15 Jostedalsbreen outlets (partly) measured during the twentieth century. In order to determine annual oscillations as well as the general trend of the glacier-front, two types of diagrams were constructed. The first shows the annual glacier-front variations (the relative positional change from one year to the next; see Fig. 8), and the second type the cumulative glacier-front variations (i.e. the total change of glacier position to a fixed point set as zero representing the glacier-front position for the first year the position was measured (see e.g. Fig. 7 and Winkler 1994 for the complete series of both types of diagram). If two or three marks existed at some glaciers and different values for different sections of the glacier tongues were indicated in the annual reports, the mean was used to calculate the annual glacier-front variations. This procedure is commonly applied to glacier-front measurements worldwide and, as experience during many decades of glaciological research has shown, the loss of accuracy is negligable due to compensation by the glacier tongue itself in subsequent years (e.g. a stronger retreat on one side of a glacier-front can easily be compensated in the following year by a stronger retreat on the other side; dramatic changes in glacier tongue morphology are rare and are described in the remarks added to every annual report). In a few cases, photographs taken at the time help to decide whether there were important changes in glacier tongue morphology.

The glacier-front variations of the Jostedalsbreen outlets cannot be presented here without noting that mass balance data are far more suitable for characterisation of the interaction between climate and glaciers than data of glaciers-front variations. Among the many limiting factors which have to be controlled in the interpretation of glacier-front variation data, the response time is one of the most important (Kuhn 1981,1989, Winkler 1994). In addition, glacier morphology and relief have to be taken into account. Mass balance data from Jostedalsbreen as a continuous record are, however, only available for Nigardsbreen. Even if these glaciological data help to increase our knowledge about the impact of individual climatic elements, there is no more useful way to study the interaction between climate and glaciers during the whole of the twentieth century other than by using the available glacier-front variation data. However, in addition to their careful interpretation, consideration also needs to be given to the response time as well as to the determination of 'trends' for whole region (see e.g. Patzelt (1985) for the Swiss and Austrian Alps); correlation with meteorological parameters is possible and the results are promising (see below). In addition, the different reactions of glaciers to the same climatic fluctuations are also of great value for investigating climate-glacier interactions.

Glacier-front variations of Jostedalsbreen outlets during the twentieth century

In western Norway, nearly all glaciers reached their maximum 'Little Ice Age' position in the middle of the eighteenth century (e.g. Eide 1955, Grove 1988). For the outlet glaciers of Jostedalsbreen, this 'Little Ice Age' maximum position was also the Neoglacial one, i.e. the greatest advance following final deglaciation and the Erdalen Event (Nesje et al. 1991). At Jostedalsbreen, this term 'Little Ice Age' is far less problematic than, for example, in the European Alps where unequivocal evidence of several major Holocene advances and Medieval glacier expansion episodes means that this term cannot really be used there, and consequently there is a need for alternative terms (Winkler 1994). Although there is little historical evidence for the 'Little Ice Age' maximum around Jostedalsbreen (exceptions being Brenndalsbreen and Nigardsbreen - see e.g. Rekstad 1901, 1904, Eide 1955), lichenometric and morphological studies confirm the assumption that around or just a few years prior to AD

1750, Jostedalsbreen outlet glaciers reached their maximum positions (see Bickerton & Matthews (1993) on the timing of the maximum 'Little Ice Age' positions using lichenometry; see Winkler (1994) for some doubts on their maximum dates for Lodals- and Stegholtbreen). However, differences in glacier reaction time to climatic fluctuations as a function of individual response times revealed by the measured glacier-front variations during the twentieth century should not be neglected. Instead of transferring Nigardsbreen's date of maximum position to all other glaciers (as was done by Mottershead & Collin (1976) with their lichenometric studies at Tunsbergdalsbreen), the most probable pattern of 'Little Ice Age' maximum positions is that of glaciers reaching that position by different dates depending on their response time and other glaciological factors.

In the second half of the eighteenth century the glacier retreat was very slow and commonly interrupted by readvances and periods of stationary glacier fronts (winter advances!), evidence for which is given by the numerous and complex terminal moraine ridges close to the outermost end moraine (Andersen & Sollid 1971, Erikstad & Sollid 1986, Bickerton & Matthews 1992, 1993, Winkler 1994). During the whole of the nineteenth century there was repeated alternation between periods of glacier retreat (in part, strong retreat periods) and readvances and periods of stationary glacier-fronts, respectively, leading to an overall retreat far behind the outermost moraines. The last two decades of the nineteenth century were also characterised by retreating glaciers, although there is evidence of minor readvances at some glaciers. Bøyabreen recorded an advance somewhere between 1880 and 1888 based on a comparison of historical photographs; and indications of advance at the end of the last decade of the nineteenth century have been reported for Supphellebreen and a few other glaciers (Rekstad 1900, 1901, 1904, Øyen 1906). Just at the time when annual measurements began, a more important readvance started at most of the outlet glaciers of Jostedalsbreen. Unfortunately, due to time spans of several years between front position measurements in the first years of regular survey, the year when the readvance actually started is not always known; and also the advance distance cannot be calculated at these particular glaciers.

The range of known starting points of the first twentieth century readvance is 1902 - 1905 (Table 1). Historical photographs taken by J.Rekstad (Fotoarkiv NGU, Trondheim) give a clear visual impression of that readvance (see below), accompanied by additional indications of a widespread increase also in ice volume on smaller glaciers on and around the Jostedalsbreen ice-cap not covered by the annual measurements. Even though not all glaciers participated in this readvance, the overall evidence clearly shows that the readvance was not a phenomenon restricted to a few glaciers but a readvance on a regional scale. The differences in glacier-front variations between the Jostedalsbreen outlets can easily be traced back to individual response times as there is a distinct pattern of smaller and steeper glaciers showing remarkable advance distances (e.g. Bergsetbreen, Bøyabreen, Melkevollbreen) compared to longer and less steep glaciers which hardly showed the overall advance during that period, with only single years of advance or no advance at all (e.g. Fåbergstølsbreen, Lodalsbreen, Nigardsbreen, Stegholtbreen, Tunsbergdalsbreen; see also appendix).

A series of three photographs of Bergsetbreen taken in 1899, 1903 and 1907 gives a clear idea of the glacial dynamics of that readvance (Figs. 2 - 5). As there was a frontal retreat (112.5 m) between 1899 and 1903, the photographs reveal a clear increase in ice volume of the icefall/upper part of the glacier tongue, whereas the lower glacier tongue is still very flat, without crevasses and showing all the typical features of a retreating glacier. Between 1903 and 1907, 60.6 m of glacier advance were measured at the glacier-front and the photograph taken in 1907 exhibits an increased ice volume of the lower tongue accompanied by a deeply crevassed frontal section (see also Fig. 6). The readvance, which was no more than a transfer of ice masses from the ice-cap to the lower glacier tongue, is the only possible glacial dynamic interpretation. This explains why the longer glaciers with their long response times (Table 2) did not participate in the

glacier	1. readvance	distance	2. readvance	distance
Austerdalsbreen	(1905) - 09*	62.5 m	no data	no data
Bergsetbreen	(1903) - 11*	145.7 m	1922 - 31	127.0 m
Bødalsbreen	(1900) - 12*	47.7 m	1922 - 30	62.0 m
Bøyabreen	(1904) - 11*	133.5 m	1921 - 31	164.0 m
Brenndalsbreen	1905 - 13	96.0 m	1922 - 32	73.0 m
Brigsdalsbreen	1904 - 10	78.2 m	1921 - 31	66.5 m
Kjenndalsbreen	(1907) - 09*	44.0 m	1922 - 32	190.5 m
Melkevollbreen	1902 - 11	177.0 m	1922 - 29	208.1 m
Supphellbreen	(1898) - 12*	95.5 m	1921 - 31	91.8 m
Vesle Supphellbreen	1902 - 11	148.0 m	1922 - 31	115.0 m
Fåbergstølsbreen	(1907) - 10*	24.9 m	1922 - 30	112.0 m
Lodalsbreen	no advance	-	1925 - 29	-5.0 m+
Nigardsbreen	(1903) - 11*	-8.9 m+	1924 - 30	48.0 m
Stegholtbreen	(1903) - 10*	26.3 m	1922 - 28	36.5 m
Tunsbergdalsbreen	1910/11		no advance	-

Table 1. Advance distances for the two advances in the first half of the twentieth century. The outlet glaciers are classified according to their response times (* - start of advance unknown; + - net retreat during the advance period).

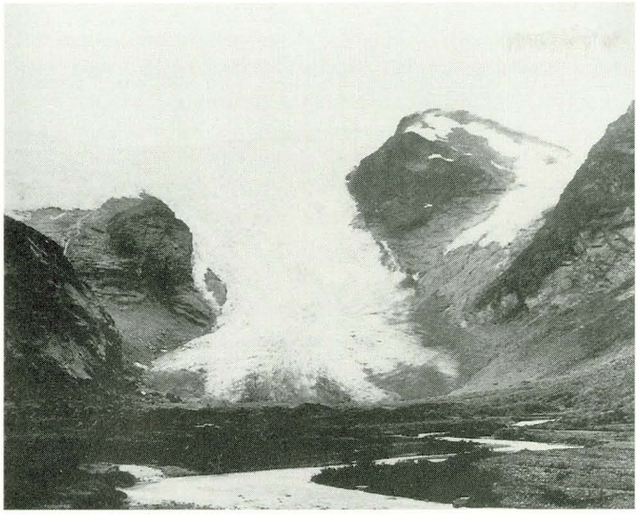

Fig. 2. Bergsetbreen, photographed by J.Rekstad 14.09.1899 (Fotoarkiv NGU Trondheim [C 30.125]).

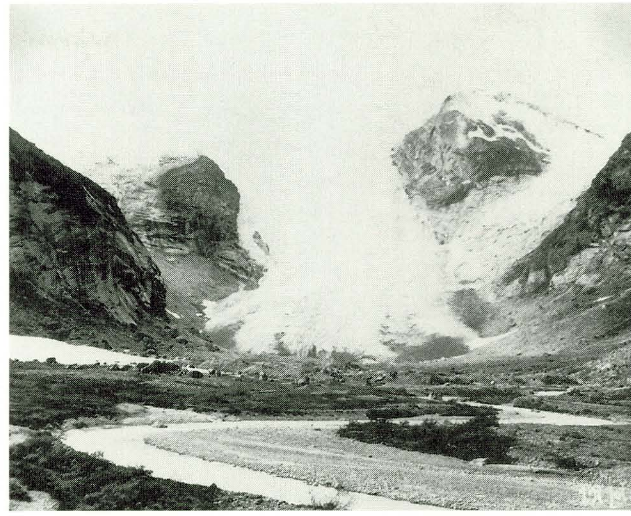

Fig. 3. Bergsetbreen, photographed by J.Rekstad 11.09.1903 (Fotoarkiv NGU Trondheim [C 30.128]).

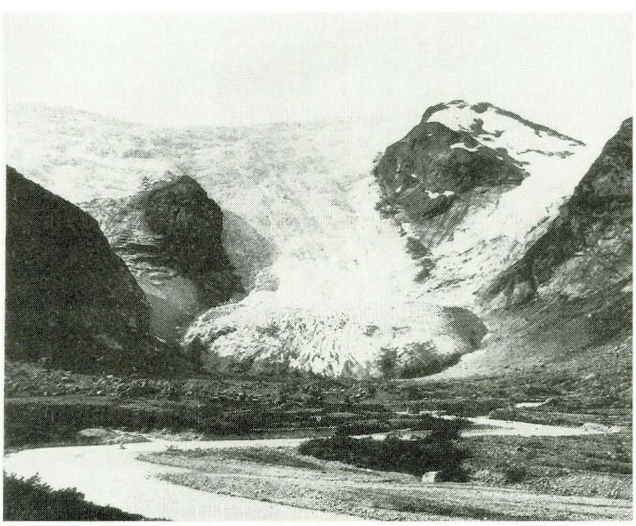

Fig. 4. Bergsetbreen, photographed by J.Rekstad 20.08.1907 (Fotoarkiv NGU Trondheim [C 30.131]).

Fig. 5. Bergsetbreen, photographed by S.Winkler 20.08.1995.

Table 2. Response times and classification of the outlet glaciers measured (* – classification mainly based on oscillations during the first half of the twentieth century).

group 1:	
response time 2 years:	Suphellebreen
response time 3 years:	Bødalsbreen, Bøyabreen, Brenndalsbreen, Brigdalsbreen, Kjenndalsbreen, Melkevollbreen
response time 4 years:	Austerdalsbreen*, Bergsetbreen, Vesle Supphellebreen
group 2:	
response time c. 25 years:	Fåbergstølsbreen, Lodalsbreen, Nigardsbreen, Stegholtbreen
group 3:	
response time c. 35 years:	Tunsbergdalsbreen

minor readvance that culminated after a few years between 1909 and 1913.

After culmination of the first readvance, a short period of retreat was registered at the glaciers up to 1921/22 (single years of advance were registered at Supphellebreen, Stegholtbreen, Nigardsbreen and Fåbergstølsbreen). Then, a second readvance started, again at nearly all outlets of Jostedalsbreen. As during the first readvance, there were differences in reaction between the glaciers covered by the annual measurements resulting from differences in individual response times. Again, aspect and local climatic factors seem to have been of negligible influence compared to the response time of the glaciers and their morphology. Between 1929 (or 1928) and 1932 this second readvance ended.

There is no distinctive general difference in duration

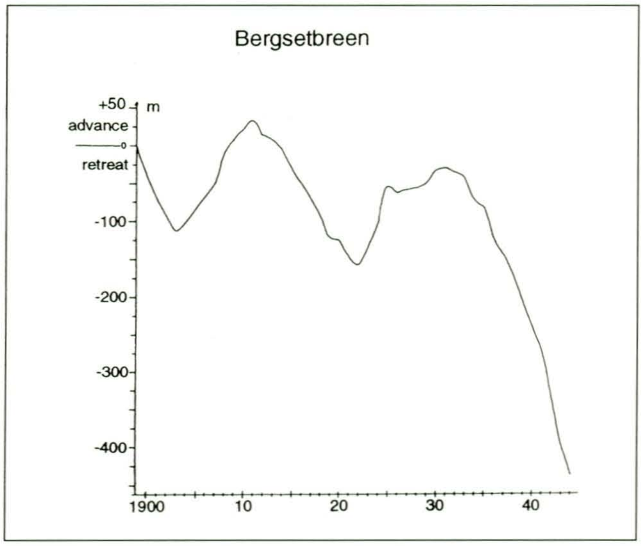

Fig. 6. Bergsetbreen, cumulative glacier-front variations (data, for Figs. 6-10, taken from Rekstad, Fægri, Liestøl and NVE).

and advance distance between the two readvances of the first half of the twentieth century. The second readvance is presumed to have lasted one or two years longer than the first one, but because the starting point of the first readvance is not precisely delimited at most of the Jostedalsbreen outlets, a definitive statement on its duration is not possible. Whether the first or the second readvance led to a greater distance of glacier-front position change between the glaciers is uncertain. At the majority of the smaller glaciers, the total advance distances of the first and second readvance were quite similar.

A remarkable difference occurred at the larger glacier tongues of Fåbergstølsbreen and Nigardsbreen with a much stronger advance during the second readvance than during the first one. Apart from this, the same major differences in reaction between the longer and the shorter glacier tongues as during the first readvance were observed. At the longer, as at the smaller glacier tongues, the second readvance was commonly interrupted for one or two years, but no distinctive pattern of years of overall interruption can be traced. It seems, simply, that the second readvance had a slightly higher magnitude at the longer glaciers. Apart from the direct climatic impact on mass balance and glacier-front variation, this might have been caused by the longer response time of these glaciers which was of such a length that the first climatic impact (first readvance) added to the second readvance. At the shorter glacier tongues, the maximum position of the second readvance was mostly located a few tens of metres proximal to the ice-front position of the first one, because of the retreat during the period 1910 - 1920 exceeding the advance distance of the first readvance. Only at Bøyabreen did the glacier-front position of 1931 reach the position of 1911; and on some parts of the glacier foreland causing the formation of a multi-ridged end moraine system (Fægri 1934a, Winkler 1994). Supphellebreen was the only permanently observed Jostedalsbreen outlet reaching farther down-valley during the second readvance and consequently overriding its terminal moraine built up around 1911. This behaviour must be viewed in the light of Supphellebreen's special glacier morphology, since it is a regenerated glacier.

Without exception, the mid-twentieth century was characterised by the extensive retreat of all outlet glaciers from Jostedalsbreen. Annual retreat distances of more than 100 m were measured where special conditions were met (narrow glacier tongues descending through steep valley heads or gorges: Brenndalsbreen, Kjenndalsbreen or Melkevollbreen; proglacial lakes: Brigsdalsbreen, Bødalsbreen and Nigardsbreen). However, as this excessive retreat occurred at all the Jostedalsbreen outlet glaciers, regional or local influences of glacier morphology, proglacial lakes or relief have to be classified as fairly important secondary factors augmenting a retreat caused by the climatic conditions during that period. Unfortunately, at many glaciers annual observations / measurements had ceased during this period of strong glacier retreat.

The retreat of the mid-twentieth century is very remarkable for its magnitude. In only a few decades, the glacier tongues melted further back than they had done in the preceding 180 years up to 1930 following the 'Little Ice

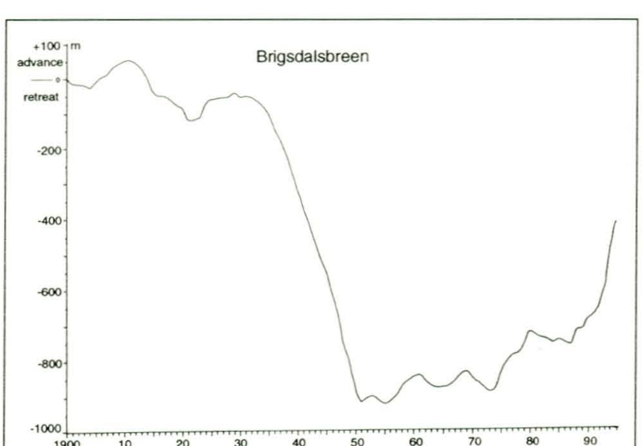

Fig. 7. Brigsdalsbreen, cumulative glacier-front variations.

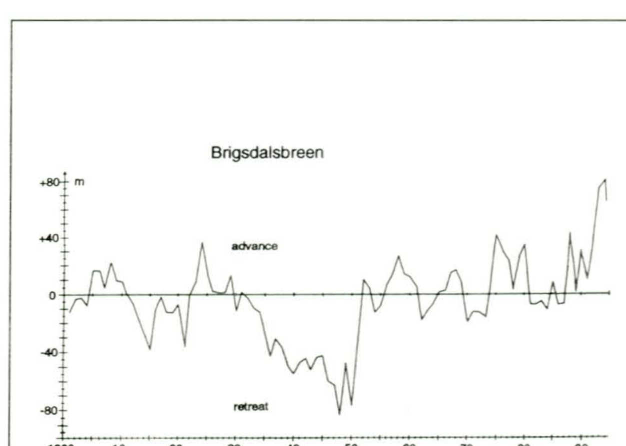

Fig. 8. Brigsdalsbreen, annual glacier-front variations.

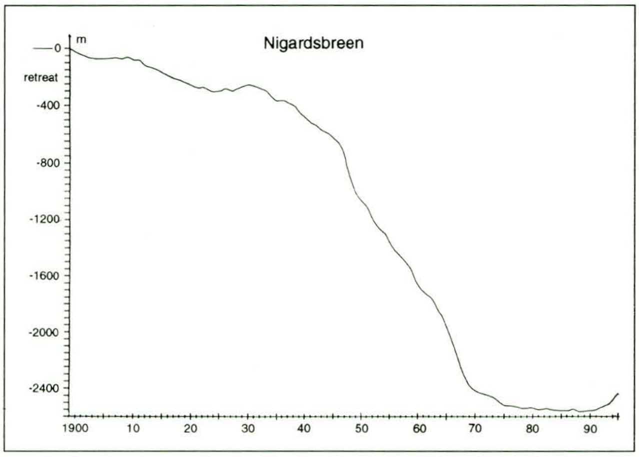

Fig. 9. Nigardsbreen, cumulative glacier-front variations.

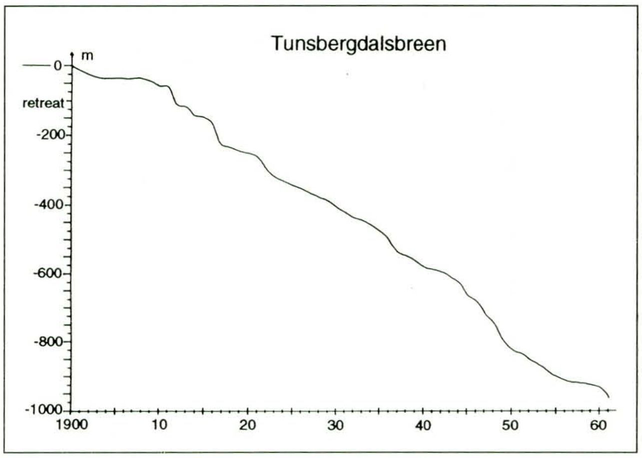

Fig. 10. Tunsbergdalsbreen, cumulative glacier-front variations.

Age' maximum. Although this strong retreat was observed at every glacier, even without continuous annual measurements it becomes clear that there were differences between the longer and the shorter glacier tongues. The strongest annual retreat of the small glaciers, marked by high retreat distances up to 100 m and more, took place during the early or late 1940's (e.g. Brenndalsbreen, Kjenndalsbreen and Brigsdalsbreen, which showed high retreat distances as early as 1935 due to the influence of a calving glacier-front on the proglacial Brigsdalsvatnet; see Figs. 7 & 8). At the longer glacier tongues, the maximum retreat was recorded considerably later during the late 1960's (Fåbergstølsbreen, Stegholtbreen, Lodalsbreen - prior to observations which stopped around 1970). Nigardsbreen was also exposed to maximum retreat during the 1960's, but a second maximum rate of retreat was observed during the late 1940's, probably caused by the special glacial dynamics of the floating calving front of the glacier on Nigardsvatnet (Fig. 9). The only glacier continuously measured until 1970 without any definite retreat maximum is Tunsbergdalsbreen (Fig. 10). A simple, but logical explanation for that observation is that the long response time in this case exceeded the response times of the other larger glacier tongues by 10 years or slightly more. As the difference in response times between shorter and longer glacier tongues (see below) is very clearly marked by the dating of the maximum retreat in the middle of the twentieth century, the maximum retreat of Tunsbergdalsbreen is likely to have occurred later during the 1970's when there were no continuous measurements.

Table 3. Recent advance distances for selected outlet glaciers (a – annual measurements (NVE); b– field observations and air photograph/topographical map analysis: start of advance unknown).

glacier	period	advance
(a)		
Brigdalsbreen	1955 - 95	498 m
	(1987 - 95)	339 m
Nigardsbreen	1988 - 95	124 m
(b)		
Bergsetbreen	1966 - 95	c. 250 m
Brennedalsbreen	1966 - 95	250 - 300 m
	(1984 - 95)	c. 200 m
Kjennedalsbreen	1984 - 95	c. 300 m
Bødalsbreen	1984 - 95	150 - 200 m

In the 1960's, at the time when the mass balance studies started on Nigardsbreen, the retreat gradually came to an end, first on the smaller glaciers. Again in conjunction with the specific response times, the increasing ice mass of the glacier plateau of Jostedalsbreen created stationary glacier-fronts. These were followed by advances which actually culminated in an impressive glacier advance exceeding both readvances of the early twentieth century; and locally nearly attaining annual advance distances not recorded since the maximum 'Little Ice Age' advance (Figs. 11 - 14, Table 3). As the annual measurements at most of the smaller glacier tongues had ceased during the middle of the twentieth century, the present author compared topographic maps and aerial photographs in order to obtain a brief indication of the magnitude of that advance on several small glacier tongues. Apart from Brigsdalsbreen with its continuous record showing a considerable advance (210 m advance 1992 - 1995; 339 m advance 1987 - 1995 and 498 m advance 1955 - 1995) and leading to its classification as 'advance' (and not just 'readvance'), similar strong advances actually occur at Bergsetbreen, Brenndalsbreen, Bødalsbreen and Kjenndalsbreen (Table 3). In addition, other smaller glaciers clearly increased in ice volume, as for example at Bøyabreen (the upper, active glacier tongue again reaching the valley bottom and the lower, inactive 'glacier tongue'/ice-snow-debris-complex itself developing into an active glacier-like form), Supphellebreen (lower part increasing in volume) and Melkevollbreen (advancing considerably down the narrow gorge of its valley head).

At the time that the smaller glaciers had already stopped their retreat, the larger glaciers still experienced a strong retreat that did not slow down until the late

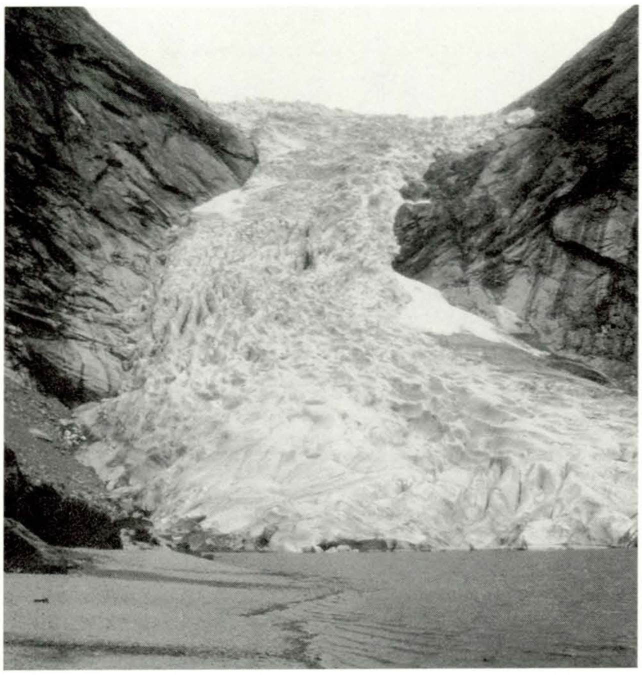

Fig. 11. Brigsdalsbreen, photographed by S.Winkler 11.08.1990

1970's. However, since c. 1975, most of the larger glacier tongues underwent a period of more or less stationary glacier-fronts (e.g. Nigardsbreen) or at least a comparable slow retreat (Fåbergstølsbreen, Stegholtbreen). Just recently, the advance which has been observed for a long time at the shorter glacier tongues also became visible at the longer glacier tongues. However, increasing ice velocity, positive mass balances during recent years, increasing dissection of glacier tongues by crevasses, and increasing ice volume in the upper and lower glacier tongues (e.g. at Nigardsbreen) are thought to be clear indicators of an increasing magnitude of an advance in the near future. In 1995, almost all glacier tongues around Jostedalsbreen were in a state of advance, for both the shorter and the longer glacier tongues, and for the annually measured glaciers as well as those not included in annual observations.

Comparing the glacier-front variations of the outlet glaciers of Jostedalsbreen during the twentieth century, significant types of glacier-front oscillation behaviour can be differentiated and a classification of the glacier tongues has become necessary. All smaller outlet glaciers with short glacier tongues and steep ice falls show very similar glacier-front variations during the first half of the twentieth century. Only at Brigsdalsbreen is there a continuous record up to the present, but this can be taken as a representative model of the oscillations of smaller outlet glaciers during the last few decades. Among these glaciers there is no indication of any great influence of aspect or local climatic factors. This is remarkable because of registered climatic differences between the valleys on different sides of Jostedalsbreen (Østrem et al. 1976, Nesje 1989, Aune 1993, Førland 1993). However, as a result of the uniform accumulation area of the glacier plateau, non-parallel deviations from the means of summer temperature and winter precipitation recorded at different locations around Jostedalsbreen seem to be far less important than glacier size, morphology and resulting response time.

It is possible to determine the response time of the Jostedalsbreen outlets by correlation analysis of their glacier-front variations, as well as of combined glacier-front variations and meteorological data (see below). The results for the smaller glaciers give common response times in the range 2 - 4 years (Table 2). For most of the glaciers, a calculated response time of 3 years provides the best fit to the winter precipitation and summer temperature records, a result already shown by Nesje (1989) and Nesje et al. (1995) at Brigsdalsbreen. The larger glacier tongues show much longer response times in the

Fig. 12. Brigsdalsbreen, photographed by S.Winkler 30.08.1995.

Fig. 13. Kjenndalsbreen, photographed by S.Winkler 09.09.1991.

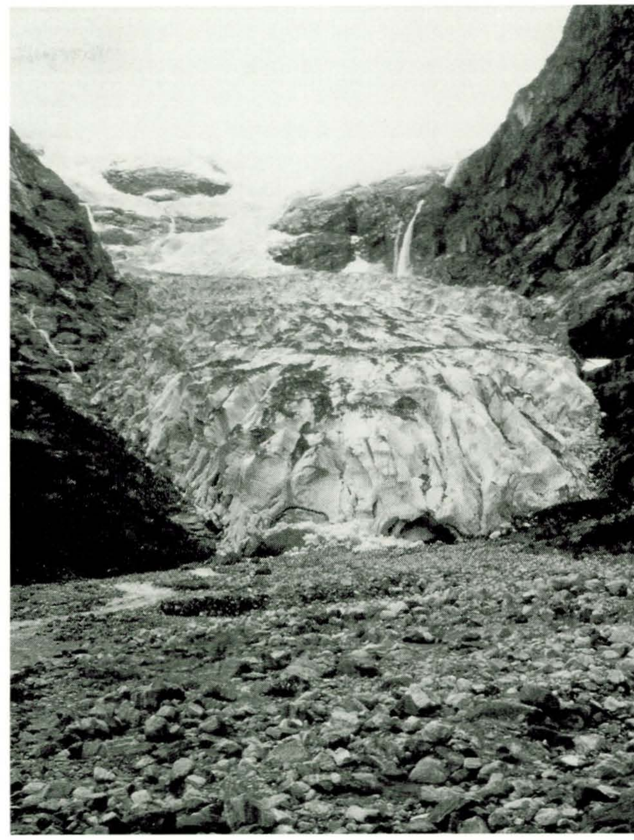

Fig. 14. Kjenndalsbreen, photographed by S.Winkler 31.08.1995.

order of 21 - 26 years delay compared to Supphellebreen (i.e., 23 - 28 years to the climatic impulse; see Winkler 1994). Owing to smaller correlation coefficients, the exact response times are to some extent uncertain, but a c. 25 years response time is assumed to be most realistic for the longer Jostedalsbreen outlets, as previously demonstrated by Nesje (1989) for Fåbergstølsbreen and Stegholtbreen. Among the larger glaciers, there are only small differences in response times (analogous to the smaller glaciers). Stegholtbreen and Fåbergstølsbreen show identical response times and very similar glacier-front variations (contrasting with quite different lichenometric dates of the 'Little Ice Age' maximum suggested by Bickerton & Matthews 1993). In the case of Tunsbergdalsbreen a longer response time of 35 - 40 years has been recorded, due to its size as the largest outlet of Jostedalsbreen. However, even if the glacier-front variations of Lodalsbreen and Tunsbergdalsbreen are quite similar (see above), a correlation of the whole glacier-front variation record of the twentieth century leads to the classification of Lodalsbreen in the group of larger glaciers (e.g. Nigardsbreen or Stegholtbreen). Although they show no important deviation from the general trend, proglacial lakes causing calving glacier-fronts have at least to be taken into account when the glacier-front variations of such glaciers are interpreted. The first maximum of retreat during the 1940's at Nigardsbreen not recorded at the other longer glacier tongues might be the result of an influence of the proglacial lakes, as well as the early maximum retreat of Brigsdalsbreen and its early (and comparably strong) oscillating advance during the 1950's, 1960's and 1970's and can be traced back to the calving glacier-front. At Austerdalsbreen, the break in the record makes it difficult to give a confirmed response time. Particularly for the first readvance of the twentieth century, this glacier behaved like the shorter glacier tongues. However, considering the recent advance, Austerdalsbreen has reacted more like a longer glacier tongue with an advance just starting a few years ago (1991). Individual glacier morphology and the extraordinary cover of supraglacial debris (causing the formation of a dead-ice/moraine-complex in front of the active part of the glacier tongue) are assumed to be responsible for this different reaction.

The twentieth century glacier-front variations of Jostedalsbreen have not been synchronous with all other glacier variations in southern Norway. In particular, the climatically more continental mountain glaciers in Jotunheimen behaved in a different way. There was only one readvance interrupting the overall retreat during the twentieth century, around or prior to 1920, i.e. at the time the Jostedalsbreen outlet glaciers underwent a phase of retreat in between the two readvances of the first half of the twentieth century (see Winkler 1994 for more details). Although the dating of that readvance is uncertain, due to a break in the annual observations in Jotunheimen,

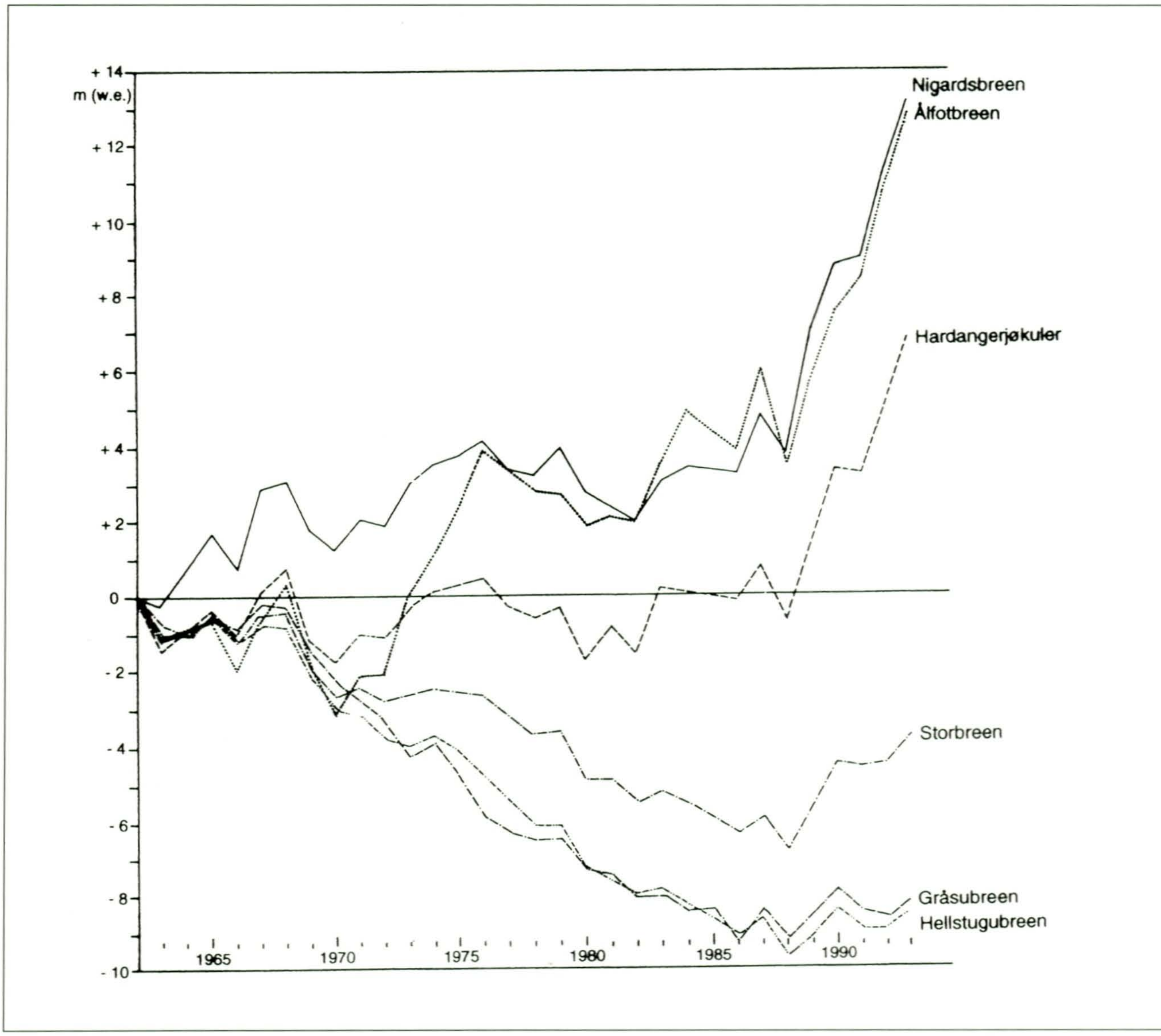

Fig. 15. Cumulative net balances of 6 glaciers in southern Norway (modified after Østrem, Dale-Selvig & Tandberg 1988; data from NVE). The 'vertical profile' is from west (top) to east (bottom), i.e. the glaciers that increased in volume are located in the west; and those that decreased, in the east.

there is no correlation of glacier-front oscillations during the first three decades of the twentieth century between Jostedalsbreen and Jotunheimen. However, the retreat period during the middle of the twentieth century was also recorded in Jotunheimen, but the annual retreat distances were relatively smaller than at Jostedalsbreen. Mass balance studies at Storbreen, Hellstugubreen and Gråsubreen (Østrem et al. 1991) showed an overall ice mass decrease over recent decades (only the very last balance years were slightly positive in some parts of Jotunheimen; Fig. 15). In contrast to Jostedalsbreen, there is no actual advance in Jotunheimen, with the exception of more or less stationary glacier fronts during the last few years (Winkler 1994), especially in the western part, e.g. Styggedalsbreen/Hurrungane and Storbreen/Visdalen.

Meteorological factors causing glacier-front oscillations

For a number of reasons, glacier-front variations are less suitable for the characterisation and analysis of glacier-climate interaction than mass balance data as the number of possible non-climatological/-meteorological factors influencing a 'pure climatic signal' of the glacier behaviour is larger. In addition, the individual impact of different meteorological factors and the significance of special meteorological parameters is often quite accurately determined by studying both annual mass balance and accumulation and ablation (winter and summer balances). Energy balance studies (i.e. determination of the contribution of single ablation factors such as solar radiation or condensation) give valuable support to mass balance investigations (e.g. Moser et al. 1986). As this glaciological research is unfortunately restricted to only a few glacier tongues (at Jostedalsbreen, with few exceptions only at Nigardsbreen), and as there are no mass/energy balance data for Jostedalsbreen dating back more than 30 - 35 years, the identification, characterisation and analysis of climatic/meteorological factors forcing twentieth century glacier-front variation of Jostedalsbreen are limited. Although some promising attempts have been made so far (see below), just a brief account of the results found in the literature and of studies by the present author is given here.

One of the first attempts to calculate the mass balance variations of Jostedalsbreen was made by Rogstad (1941, 1952) using runoff and meteorological data. He calculated higher summer temperatures (at Oppstryn) measured during his observation period than were necessary to melt winter snow accumulation recorded in the same time interval (1901 - 1950; a calculated mean equilibrium summer temperature for that period 0.85°C lower than the recorded one: 11.76°C). In more detail, he registered an oscillation between short periods of volume increase (positive mass balances) and volume decrease (negative mass balances), corresponding to the two readvances and the intervening period of retreat during the first half of the twentieth century (bearing in mind glacier response times). Rogstad's results reveal that both summer temperature (below average) and winter precipitation (above average) were favourable for a glacier volume increase and resulting readvance. However, it is not possible to decide whether one of these two forcing meteorological elements had a significantly higher influence (only for the period 1925-40 do summer temperatures seem to be clearly more important).

Although Rogstad's results have been criticised because of a less precise marking of accumulation/drainage areas for the gauging station and neglecting the effect of calving at Brigsdalsbreen (Østrem & Karlén 1963), the trend demonstrated by his results has some validity (see below). Apart from Rogstad, other authors made comments on the forcing meteorological factors of glacier-front variations at Jostedalsbreen (e.g. Rekstad 1900, Fægri 1934a). Unfortunately, there is no consensus in their results and conclusions (winter precipitation and summer temperatures are alternately proposed as the most important factor).

In a recent study, Nesje (1989) concluded that both major meteorological elements, winter precipitation and summer temperature, are responsible for the two readvances of the first half of the twentieth century by intensifying their individual impact (i.e. winter precipitation above and summer temperatures below the average means) without the possibility of distinguishing whether one of these elements is more important than the other. A similar effect of the two major meteorological elements intensifying their impact by synchronous fluctuations, but now in an unfavourable manner for Jostedalsbreen, is shown by Nesje for the middle of the twentieth century when summer temperatures above and winter precipitation below average caused a fast retreat of the glacier tongues. Decreasing summer temperatures since the 1960's and 1970's in conjunction with increasing winter precipitation caused the glaciers to grow and advance again. Over the whole period studied, Nesje found a higher correlation between summer temperatures and glacier-front variations than between winter precipitation and position changes of the glacier tongues. However, the best correlation, not surprisingly, was found by using a calculated combined parameter of these two elements (see Nesje 1989 for more details).

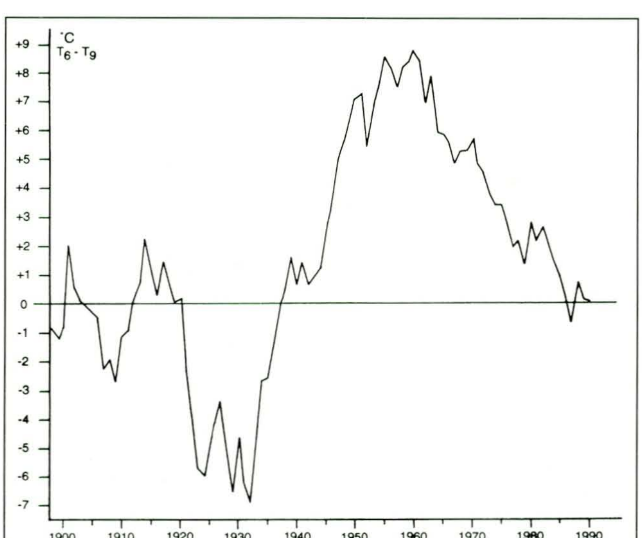

Fig. 16. Cumulative deviations of summer temperature (T6 - T9) from the mean of the observation period (12.2 °C) for Oppstryn (data from DNMI).

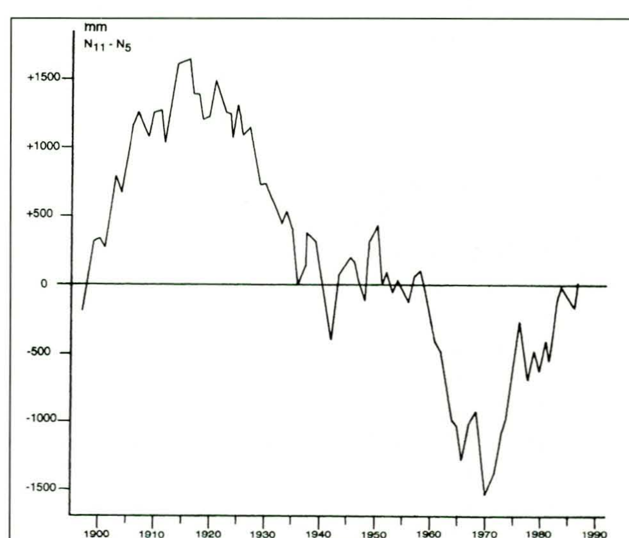

Fig. 17. Cumulative deviations of winter precipitation (N11 - N5) from the mean of the observation period (709.9 mm) for Jostedal (data from DNMI).

In the opinion of the author, the better correlation for summer temperatures is most likely to have been caused by the particularly rapid retreat during the middle of the twentieth century when summer temperature deviations from the average mean were much higher than comparable deviations of winter precipitation from the average mean, and winter precipitation had less influence on the mass balances (Figs. 16 & 17). Another factor to be taken into account is the common observation that glaciers are not assumed to be in a state of equilibrium with the present-day climatic conditions (Kuhn 1984). Owing to the delayed response of glaciers to major and long-term changes of the climatic environment, the state of the glacier (i.e., its position and volume) prior to an advance or retreat period always shows an influence on the actual mass balance. It seems logical that the outlets of Jostedalsbreen at about 1930 still contained some excess mass left over from their 'Little Ice Age' advance that was not sufficiently reduced during the nineteenth century due to frequent small readvances and stillstands of the glacier-fronts. As a consequence, the glacier tongues were larger and located farther down-valley than would be expected for the climate around 1920/30. Thus, the rapid retreat during the middle of the twentieth century could have been influenced by these non-equilibrium glacier-front positions and highly negative mass balances prevailing as a result of the large natural ablation area (when the glaciers were more easily affected by higher summer temperatures). It should be noted that such considerations also apply in other glacier regions such as the Austrian Alps, where the retreat observed during the middle of the twentieth century was far more rapid than would be expected from the summer temperature deviations.

In a recent study, Winkler (1994) used primarily mass balance data from Nigardsbreen and other glaciers in southern Norway to characterise and analyse the impact of separate meteorological elements and glacier parameters (Tables 4 - 6). Although the results cannot be presented here in detail, the known similarity of individual meteorological stations around Jostedalsbreen was used to correlate meteorological parameters such as summer temperature, winter precipitation and glacier-front variation data (response time and changes in the system of relevant meteorological and non-meteorological factors were taken into consideration).

Although the results carry a degree of uncertainty, the present author's results support the conclusions of Nesje and Rogstad that it is not possible to differentiate between winter precipitation and summer temperatures in order to determine which meteorological factor had the most significant impact on the glaciers. However, the rapid retreat during the middle of the twentieth century was primarily the result of higher summer temperatures. In addition, best-fit regression reconstructions of the mass balance of Nigardsbreen using meteorological parameters/stations and mass balance data suggest that the different states of the glacier (larger and lower glacier tongues) had a strong influence and caused an even more rapid retreat; and when numerous regressions were tried, calculated negative mass balances and ice mass reduction were never of the magnitudes observed during that period. After 1970, winter precipitation clearly became the most important meteorological element, especially during the recent years of very large winter snow accumulation.

However, these modelling exercises are very complex. If, for example, correlations over shorter periods are calculated, there are significant differences. Taking Brigsdalsbreen as an example, glacier-front variations correlated with winter precipitation (January - April)

Table 4. Correlation coefficients for winter precipitation - winter/net balance at Nigardsbreen (N = mean of monthly precipitation, 1 = January, etc.).

station	5056	5535	5545	5573	5584	5870
			winter balance			
N10 - N5	0.71	0.55	0.70	0.77	0.81	0.72
N11 - N5	0.74	0.71	0.74	0.83	0.81	0.81
N11 - N4	0.74	0.70	0.74	0.83	0.81	0.79
N12 - N5	0.77	0.80	0.70	0.82	0.79	0.82
N12 - N4	0.76	0.81	0.72	0.83	0.80	0.80
N1 - N4	0.73	0.89	0.81	0.85	0.81	0.82
			net balance			
N10 - N5	0.57	0.44	0.53	0.67	0.65	0.60
N11 - N5	0.64	0.69	0.59	0.73	0.71	0.70
N11 - N4	0.63	0.67	0.58	0.71	0.69	0.67
N12 - N5	0.66	0.67	0.67	0.70	0.67	0.68
N12 - N4	0.62	0.68	0.68	0.69	0.65	0.65
N1 - N4	0.64	0.74	0.64	0.71	0.67	0.70
N10 - N9	0.59	0.55	0.54	0.71	0.67	0.62
N5 - N10	0.14	0.31	0.19	0.30	0.26	0.06

5056 - Bergen-Fredriksberg 5535 - Luster
5545 - Jostedal 5573 - Sogndal-Selseng
5585 - Brigsdal 5870 - Oppstryn

Table 5. Correlation coefficients for summer temperature - summer/net balance of Nigardsbreen (*– short observation record; T = mean monthly temperature, 5 = May, etc.).

station:	summer	net balance
[5056] Bergen	-0.79 (T6 - T8)	-0.70 (T6 - T8)
[5523] Fannaråken	-0.82 (T6 - T8)	—
[5529] Sognefjell*	-0.97 (T6 - T9)	—
[5535] Luster	-0.87 (T5 - T8)	-0.89 (T5 - T8)
[5543] Bjørkehaug*	-0.82 (T6 - T8)	—
[5584] Fjærland	-0.23 (T6 - T10)	—
[5870]Oppstryn	-0.75 (T6 - T8)	—

Table 6. Correlation coefficients for winter precipitation (N1 - N4) at Oppstryn and the winter/net balance at Nigardsbreen.

period	winter	net balance
1962 - 66	r = +0.99	r = +0.95
1967 - 71	r = +0.87	r = +0.87
1972 - 76	r = +0.81	r = +0.75
1977 - 81	r = +0.40	r = +0.51
1982 - 86	r = +0.79	r = +0.82
1987 - 90	r = +0.75	r = +0.59

recorded at Oppstryn (empirically found to be the best fitting parameter), the correlation coefficients for 10-year periods varied between $r = +0.8176$ ($p < 0.05$) and $r = -0.0136$ ($p > 0.05$). This influence of individual meteorological factors showing strong variations over short intervals leads to the somewhat disappointing statement that it will be very difficult (or perhaps impossible) to reconstruct mass balance series. In some regions there has been progress, for example in Austria, as a result of the clear relationship between summer snow fall frequency/summer temperature and glacier mass balance as undoubtedly the most important meteorological factors (Fliri 1964, 1990). However, at Jostedalsbreen with its maritime climatic environment and consequent complicated interactions between air temperature and precipitation, there still remains much work to do before reliable reconstructions can be made.

Implications and conclusions

(1) The glacier-front measurements of Jostedalsbreen have offered a unique opportunity to study the reaction of several adjacent glacier tongues during the twentieth century. The following patterns of glacier-front variations have occurred: (a) In the first half of the twentieth century, two readvances occurred at most of the smaller Jostedalsbreen outlets. Both readvances lasted 6 - 10 years and the advance distances were mostly similar. The readvances culminated around 1910/11 and 1930/31. They were interrupted by a short period of retreat during the period 1910-1920. At the larger glacier tongues, two readvances were either only recorded as advances of one year or no advance tendencies were recorded at all. (b) After 1930, a period of rapid retreat was measured at all Jostedalsbreen outlets. At the smaller glaciers, the years of greatest retreat distances occurred during the 1940's for the larger glaciers during the 1960's. (c) The retreat phase ceased at the smaller glaciers in the 1960's (for some glaciers as early as the 1950's). After a period of stationary glacier-fronts an advance phase occurred which lasted until the present; and this has increased considerably in magnitude in recent years. At the larger glaciers the retreat slowed down during the 1980's. After several years of nearly stationary glacier-fronts, even the larger glaciers also started to advance at the beginning of the 1990's and presumably they will reach the rate of advance characteristic of the smaller glaciers; this is indicated by an impressive increase in the ice mass of the lower tongues, an increasing number of crevasses and an increasing ice velocity.

(2) There are important differences in the reaction of glacier tongues of different size throughout the twentieth century. As a result of the influence of glacier size and morphology, and resulting individual response time, smaller glaciers were involved in two readvances in the first half of the century and underwent the most pronounced retreat period earlier than the larger glaciers. The same 'delayed' reaction of larger glaciers is evident with the recent advance. Correlation of the glacier-front variations allows a classification of three different groups of glaciers based on their differences in response time: (a) Similar small and steep glaciers (e.g., Brigsdalsbreen, Bergsetbreen) with response times of 2 - 4 years. (b) Larger glacier tongues reacting sluggishly, with response times of about 25 years (e.g. Nigardsbreen). (c) Tunsbergdalsbreen, as the largest Jostedalsbreen outlet, can be classified as an exception with a response time of at least 35 years. However, other glaciological and climatological factors such as aspect show no important influence on the glacier-front oscillation behaviour, as glaciers of one group indicated above show the same patterns of front position change independent of which side of the glacier plateau they are located.

(3) Apart from some restrictions on accuracy, glacier-front variations can be correlated with meteorological data to determine the influence of various meteorological elements and parameters. The first two readvances of the twentieth century were caused by higher winter precipitation and lower summer temperatures intensifying each other, with no possibility to decide which meteorological factor is the leading one. The fast retreat during the middle of the 20th-century was caused mainly by high summer temperatures. The actual glacier advance is clearly a result of an unusually large winter snow accumulation during recent years.

(4) In combination with glaciological data (mass and energy balances), glacier-front variations can be used to reconstruct the mass balance changes of Jostedalsbreen during the twentieth century. Unfortunately, the results of the reconstructions were not successful owing to the fact that the present relationship between mass balance and meteorological parameters is not a useful basis for regression calculations. However, it is possible that improvements in such reconstructions can be made in the future so that the available data on glacier-front variations and climatic fluctuations can be used to a greater extent than has hitherto been possible.

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APPENDIX

Cumulative glacier-front variations of all the measured outlet glaciers of Jostedalsbreen (only continuous records; for codes of glaciers, see Fig. 1; VSP = Vesle Supphellebreen).

year	AUS	BER	BØD	BØY	BRE	BRI	FÅB
1898				x			
1899		x					x
1900		...	x		...	x	...
1901		...	...	...	-18.3	-12.5	...
1902		...	...	...	-17.7	-15.5	...
1903		-112.6	...	-80.5	-21.3	-17.9	-22.0
1904		...	...	-94.0	-27.5	-26.7	...
1905	x	...	...	...	-32.5	-10.0	...
1906	+20.0	...	...	-10.5	-2.7	+6.3	...
1907	-35.0	-52.0	+29.7	+2.5	+4.5	+11.3	-57.3
1908	+48.5	-9.8	+37.2	+38.5	+29.5	+33.3	-46.6
1909	+62.5	+7.7	+38.0	+43.5	+42.5	+42.5	-35.9
1910	+46.5	+22.4	+42.2	+37.5	+57.9	+51.5	-32.4
1911	+45.0	+33.1	+46.2	+39.5	+64.8	+51.0	-49.9
1912	+42.0	+13.1	+47.7	+35.5	+59.6	+44.8	-43.9
1913	+34.0	+8.6	+35.2	+23.5	+63.1	+28.6	-57.4
1914	+24.5	-4.4	+15.0	-16.5	+47.6	-1.0	-66.9
1915	+13.0	-28.9	+8.7	-73.5	+34.6	-37.4	-71.9
1916	+8.5	-49.9	-15.7	-80.5	+27.8	-48.1	-82.4
1917	-24.6	-70.4	-20.7	-83.5	-9.7	-49.9	-99.4
1918	-55.2	-94.9	-44.2	-93.5	-36.7	-62.4	-108.9
1919	...	-121.4	-75.7	-104.5	-42.7	-75.2	-97.9
1920	-87.8	-126.9	-84.2	-141.5	-89.7	-83.5	-107.9
1921	—	-146.4	-89.2	-111.5	-105.9	-119.8	-123.9
1922		-157.9	-95.7	-96.5	-113.9	-119.8	-128.4
1923		-136.9	-85.2	-81.5	-112.1	-111.1	-47.4
1924		-106.4	-100.2	-36.5	-63.9	-74.6	-60.4
1925		-53.9	-88.2	-23.5	-74.4	-61.5	-46.9
1926		-61.9	-78.7	-10.5	-63.4	-58.7	-40.9
1927		-59.9	-76.7	-2.5	-67.4	-57.7	-31.4
1928		-57.4	-45.7	+0.5	-53.1	-56.0	-27.9
1929		-49.4	-34.7	+17.5	-44.1	-43.7	-25.4
1930		-32.4	-33.7	+22.5	-41.6	-55.2	-15.9
1931		-30.9	-35.2	+11.5	-43.8	-53.4	-17.4
1932		-36.9	-42.7	+1.5	-40.8	-56.1	-19.9
1933	x	-42.4	-62.2	-8.5	-58.3	-65.6	-28.4
1934	-36.0	-70.9	-79.2	-26.5	-78.3	-77.6	-37.4
1935	-47.5	-84.4	-89.7	-61.5	-119.3	-104.1	-40.4
1936	-83.0	-123.9	-95.7	-106.5	-158.8	-147.1	-47.9
1937	-106.0	-172.9	-120.7	-156.5	-183.8	-178.1	-122.9
1938	-117.0	-168.9	-145.2	-186.5	-227.3	-214.6	-104.4
1939	-153.0	-209.9	-189.0	-236.5	-288.8	-264.3	-133.4
1940	-191.0	-242.2	-209.0	-326.5	-350.3	-320.0	-156.4
1941	-277.0	-271.4	-219.0	-341.5	-428.3	-367.2	-189.4
1942	-464.0	-337.4	-232.0	-456.5	-472.3	-411.7	-206.9
1943	-491.0	-397.4	-336.0	-466.5	-551.8	-463.9	-259.9
1944	-522.0	-439.4	-419.5	-496.5	-665.3	-507.2	-251.4
1945	-538.0	—	-438.5	-516.5	-761.8	-549.7	-310.4
1946	-549.0		-473.5	...	-1015.8	-609.7	-336.4
1947	-566.0		-544.0	...	-1120.8	-691.9	-378.4
1948	-599.0		-570.0	-536.5	-1204.8	-755.9	-442.4
1949	-649.0		-639.0	-566.5	-1248.8	-803.6	-482.9
1950	-674.0		-710.0	-576.5	-1292.8	-880.1	-526.9
1951	-704.0		...	-581.5	-1325.3	-917.3	-553.9
1952	-724.0		751.0	—	-1342.8	-907.3	-586.9
1953	-757.0		—		1352.8	-902.6	-633.9
1954	-817.0				-1357.3	-915.6	-673.9
1955	-860.0				...	-923.6	-735.9
1956	...				-1359.3	-916.6	-769.9
1957	-907.0				-1361.3	-903.6	-805.9
1958	-950.0				-1352.3	-876.6	-865.9
1959	-988.0				-1340.3	-862.6	-911.9
1960	-1019.0				...	-850.6	-975.9
1961	-1046.0				-1333.3	-844.6	-1037.9
1962	-1067.0				-1330.3	-862.5	-1065.9
1963	-1088.0				—	-873.6	-1108.9
1964	1116.0					-880.6	-1168.9
1965	1124.0					-878.6	-1271.9
1966	1155.0					-875.6	-1409.9
1967	1156.0					-860.6	1510.9
1968	1178.0					-843.6	-1647.9
1969	-1211.0					-835.6	-1782.9
1970	-1224.0					-854.6	-1903.9
1971	-1251.0					-866.6	-1976.9
1972	-1283.0					-878.6	-2042.9
1973	-1290.0					-893.6	-2072.9
1974	-1280.0					-883.6	-2094.9
1975	-1283.0					-842.6	-2105.9
1976	-1274.0					-812.6	-2135.9
1977	-1275.0					-789.6	-2163.9
1978	-1294.0					-876.6	-2190.9
1979	-1299.0					-760.6	-2210.9
1980	-1296.0					-726.3	-2233.9
1981	-1313.0					-733.8	-2257.9
1982	-1327.0					-741.8	-2272.9
1983	-1330.0					-746.8	-2281.9
1984	-1344.0					-757.8	-2296.9
1985	-1354.0					-749.8	-2318.9
1986	-1353.0					-757.8	-2345.9
1987	-1375.0					-764.8	-2352.9
1988	-1377.0					-721.8	-2390.9
1989	-1378.0					-720.8	-2415.9
1990	-1378.0					-690.8	-2434.9
1991	-1378.0					-680.8	-2452.9
1992	-1373.0					-645.8	-2458.9
1993	-1366.0					-570.8	-2448.9
1994	-1351.0					-490.8	-2414.9
1995	-1336.0					-425.8	-2370.9

year	KJE	LOD	MEK	NIG	STE	SUP	TUN	VSP
1898						x		x
1899		x		x	...	...		...
1900	x	...	x	...	...	...	x	...
1901	...	...	-25.4	...		+6.0	...	...
1902	...	...	-48.7	...		+25.8	...	-36.8
1903	...	-74.6	-42.6	-73.5	x	-+5.3	-34.5	+29.2
1904	...	...	-48.7	...	...	+29.0	...	...
1905	...	...	-29.7	...	...	+42.5	...	...
1906	...	...	+3.5	...	...	+55.5	...	...
1907	-5.8	-146.0	+26.2	-64.5	+9.0	+72.5	-35.0	...
1908	+25.2	...	+56.3	-74.9	+19.8	+85.5	-36.3	+81.2
1909	+38.2	-173.0	+92.3	-56.4	+23.8	+93.5	-45.8	+102.2
1910	+36.2	-194.1	+121.3	-87.4	+26.3	+90.5	-60.8	...
1911	+20.2	-207.7	+128.3	-82.4	+23.9	+95.5	-57.8	+111.2
1912	+21.7	-222.7	+124.5	-122.4	+12.3	+88.5	-114.8	+95.2
1913	+11.2	-244.7	+109.7	-133.9	+2.8	+86.5	-117.8	+86.2
1914	-21.3	-267.7	+91.3	-146.4	-7.2	+75.8	-143.8	+54.2
1915	-39.8	-288.7	+56.1	-171.4	-12.2	+85.1	-147.8	+34.2
1916	-57.3	-302.7	+22.8	-191.4	-21.2	+72.8	-164.8	+27.2
1917	-93.3	-322.2	-14.2	-210.4	-35.7	+62.1	-228.8	+14.2
1918	-138.3	-317.7	-65.7	-225.9	-26.7	+61.4	-233.8	...
1919	-164.8	-325.2	-87.2	-246.4	-35.7	+54.4	-247.8	+8.2
1920	-194.3	-340.2	-102.2	-260.9	-46.7	+75.4	-251.8	-8.8
1921	-216.8	-354.7	-202.5	-277.4	-60.2	+94.4	-262.3	-41.8
1922	-232.3	375.2	-223.2	-270.4	-65.7	+132.7	-295.8	-80.8
1923	-211.8	-394.2	-285.5	-293.4	-50.2	+151.7	-318.8	-69.8
1924	-154.8	-412.2	-127.5	-306.4	-62.2	+143.7	-331.8	-33.8
1925	-101.3	-413.7	-83.5	-296.4	-28.2	+145.2	-341.8	(. . .)
1926	-90.3	-404.7	-60.6	-280.4	-22.7	+148.2	-351.8	+2.2
1927	-78.3	-437.7	-31.6	-296.4	-31.7	+159.2	-366.3	+4.2
1928	-70.8	-422.2	-32.6	-284.4	-29.2	+143.2	-376.3	-1.8
1929	-64.3	-418.7	-15.1	-264.4	-35.7	+146.2	-384.3	+11.2
1930	-51.3	-446.2	-18.9	-258.4	+42.2	+129.5	-407.3	+29.2
1931	-48.3	-467.2	-28.6	-267.4	-32.7	+117.8	-421.8	+34.2
1932	-41.8	-463.7	-32.4	-282.4	-20.7	+106.5	-433.8	+27.2
1933	-53.5	-478.2	-76.4	-297.4	-28.7	+69.5	-441.8	+9.2
1934	-108.3	-51.2	-91.4	-342.4	-38.7	+66.2	-455.3	-4.8
1935	-127.8	-524.2	-123.7	-367.4	-43.7	+31.5	-475.3	-19.8
1936	-145.3	-547.2	-162.7	-362.4	-47.7	+18.8	-501.3	-62.8
1937	-191.8	-563.2	-262.7	-379.4	-56.7	-7.9	-537.8	-102.8
1938	-230.5	-551.2	-363.2	-400.9	-57.7	-20.9	-548.3	-117.8
1939	-264.3	-571.7	-565.7	-450.4	-96.7	-33.9	-562.8	-207.8
1940	-338.3	-693.7	-588.7	-478.4	-118.7	-65.9	-581.8	-237.8
1941	-458.3	-615.7	-708.7	-519.4	-148.7	-82.9	-586.3	-307.8
1942	-496.3	-650.7	—	-538.4	-178.7	...	-591.3	—
1943	-670.3	-682.7		-576.4	-207.7	...	-607.3	
1944	...	-697.2		-586.4	-223.7	-129.9	-625.8	
1945	-1101.8	-725.7		-629.4	-239.7	-144.9	-662.3	
1946	-1081.8	-789.2		-664.4	-273.3	-148.9	-679.3	
1947	-1143.8	-823.2		-777.4	-298.7	-153.9	-722.8	
1948	-1273.8	-855.2		-917.4	-326.7	—	-745.8	
1949	...	-906.2		-1009.4	-368.7		-799.8	
1950	...	-951.2		-1056.4	-413.7		-822.8	
1951	...	-982.2		-1112.4	-442.7		-835.3	
1952	-1587.8	-1010.7		-1199.4	-465.7		-852.3	
1953	—	-1045.7		-1259.4	-509.7		-867.8	
1954		-1075.7		-1300.4	-536.7		-888.3	
1955		-1129.7		-1372.4	567.7		-900.3	
1956		-1181.7		-1425.4	-596.7		-910.3	
1957		-1208.7		-1459.4	-621.7		-916.3	
1958		-1225.7		-1508.4	-655.7		...	
1959		-1303.7		-1574.4	-705.7		-921.9	
1960		-1359.7		-1661.4	-765.7		-936.3	
1961		-1410.7		-1716.4	-782.7		-963.3	
1962		-1417.7		-1746.4	-817.7		—	
1963		-1452.7		-1881.4	-868.7			
1964		-1502.7		-1876.4	-909.7			
1965		-1622.7		...	-978.7			
1966		-1767.7		...	-1048.7			
1967		-1830.7		...	-1117.7			
1968		-1961.7		...	-1227.7			
1969		-2088.7		-2391.4	-1326.7			
1970		-2204.7		...	-1442.7			
1971		—		...	-1506.7			
1972				...	-1556.7			
1973				-2456.4	-1582.7			
1974				-2502.4	-1594.7			
1975				-2518.4	-1593.7			
1976				-2519.4	-1605.7			
1977				-2526.4	-1617.7			
1978				-2540.4	-1626.7			
1979				-2537.4	-1632.7			
1980				-2536.4	-1639.7			
1981				-2547.4	-1649.7			
1982				-2543.4	-1654.7			
1983				-2548.4	-1664.7			
1984				-2548.4	-1675.7			
1985				-2552.4	-1672.7			
1986				-2559.4	-1672.7			
1987				-2548.4	-1672.7			
1988				-2566.4	-1680.7			
1989				-2565.4	-1687.7			
1990				-2558.4	-1696.7			
1991				-2551.4	-1704.7			
1992				-2542.4	-1709.7			
1993				-2528.4	-1712.7			
1994				-2492.4	-1722.7			
1995				-2442.4	-1727.7			