

PERTURBATION OF CLIMATIC RESPONSE AT MARITIME GLACIERS?

STEFAN WINKLER and ATLE NESJE

With 13 figures and 6 tables

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Summary: Detailed analyses of mass-balance and length-variation data from maritime mountain glaciers in southern Norway reveal that some frequent assumptions of the relationship between mass-balance data and terminus response need to be reconsidered. In particular, the possibility of a ‘regime shift’ in the mass-balance drivers and the virtual absence of any frontal reaction time due to a perturbation of the dynamic response of the glacier tongue occurring around c. AD 2000 are discussed. Although above-average summer air temperatures unambiguously caused the most recent retreat, it is not clearly linked to mass-balance data. Furthermore, the maritime glaciers of southern Norway are in general not entirely determined by air temperature changes. Relative contributions of the winter balance to the annual net mass balance variations were high during the last decades of the 20th century and a considerable increase in ice mass during the 1990s was caused by increased winter precipitation. Therefore, the parameter ‘annual air temperature’ cannot be applied to explain glacier length variations.

Zusammenfassung: Die detaillierte Analyse von Massenbilanz- und Längenänderungs-Datenreihen maritimer Hochgebirgsgletscher in Südnorwegen zeigt, dass häufig verwendete Annahmen über die Beziehung zwischen Massenbilanzdaten und Längenänderungen einer kritischen Überprüfung unterzogen werden müssen. Insbesondere die Möglichkeit eines „Regimewechsels“ innerhalb der massenbilanzdeterminierenden Faktoren und die augenscheinliche Abwesenheit jeglicher frontalen Reaktionszeit durch Störung der dynamischen Reaktion der Gletscherzunge seit ungefähr dem Jahr 2000 werden diskutiert. Obwohl überdurchschnittliche sommerliche Lufttemperaturen unzweifelhaft den aktuellen Rückzug verursacht haben, ist jener nicht deutlich an die Massenbilanzdaten gekoppelt. Außerdem werden die maritimen Gletscher Südnorwegens generell nicht ausschließlich durch Lufttemperaturvariationen gesteuert. Der relative Beitrag der Winterbilanz an den jährlichen Nettobilanzschwankungen während der letzten Jahrzehnte des 20. Jahrhunderts war hoch, ein erhebliches Eismassenwachstum in den 1990er Jahren wurde durch angestiegene Winterniederschläge verursacht. Daher kann der Parameter „Jahresmitteltemperatur“ hier nicht angewendet werden, um die Gletscherlängenänderungen zu erklären.

Keywords: Glacier variations, climate change, maritime mountain glaciers, Jostedalbreen, western Norway

1 Introduction

Mountain glaciers are key indicators of global climate change (IPCC 2007), and for several aspects of sustainable development in high-mountain regions (hydro-electric energy, water supply, tourism, etc.) it is crucial to estimate future glacier variations (HUBER et al. 2005). Changes in glacier volume, area, and length are determined by the climate and related mass flux/glacier flow. Therefore, the interactions and relationships between individual meteorological and glaciological parameters need to be known before any model can be applied. Most models assume that these factors are constant over time and thus apply long-term mean data for construction of model algorithms (BAMBER and PAYNE 2004). Glacier length variations are assumed to be a dynamic response of the glacier tongue to mass-balance changes, and simulated accordingly (OERLEMANS 2001; HOOKE 2005). Analogously, cumulative glacier length changes are collected to derive estimation for annual air temperature in-

crease during the 20th century (OERLEMANS 1994, 2005). In this paper, we highlight new empirical results from maritime southern Norway that may be contradictory to some of the frequently applied assumptions regarding the relationship between metrological/climate data and glacier response, especially the representativeness of long-term average data, constant terminus reaction times, and the coupling of net mass-balance data with length changes. In particular, we want to present a hypothesis that there is the possibility of a regime shift in the mass-balance drivers and/or the mechanisms of terminus reaction at these glaciers.

2 The study area and its glaciological regime

Southern Norway is a region with detailed long-term glaciological data sets (ANDREASSEN et al. 2005; ZEMP et al. 2008). Within a distance of only 180 km along an E-W profile, important spatial dif-

ferences in mass-balance characteristics, net mass-balance trends, and length variations take place (Figs. 1, 2). Despite different absolute cumulative net mass-balance trends over the past decades (Fig. 3), relative trends of seasonal mass-balance data reveal some parallels (Tab. 1). Prominent positive or negative departures of annual seasonal and net mass balances frequently occur almost simultaneously throughout southern Norway (Fig. 4). This pattern would not be present with regionally different climate trends or a high degree of spatial differentiation of the recent climate fluctuations within this region. Therefore, the existing net mass-balance differences cannot ultimately be related to a regionally different climate development, but to a regionally different response of the mass balance at individual glaciers to comparable fluctuations of meteorological parameters caused by their different glaciological characteristics.

In general, the net mass balance at maritime (western) glaciers in southern Norway is more influenced by weather conditions during the accumulation season than during the ablation season, i.e. mainly by the amount of winter precipitation/snow accumulation (Fig. 5). The corresponding net mass balance at glaciers located farther east in a more continental climate (Storbreen, Hellstugubreen, Gråsubreen – all located in Jotunheimen) is exposed to stronger impacts of variations in effectiveness of summer ablation and summer balance (NESJE et al. 2008a). On the basis of this spatial differentiation between maritime and continental glaciers in southern Norway, application of large regional glacier samples like ‘Scandinavia’, ‘Europe’, or ‘Atlantic’ (e.g. IPCC 2007) may therefore be considered as of limited validity for specific approaches.

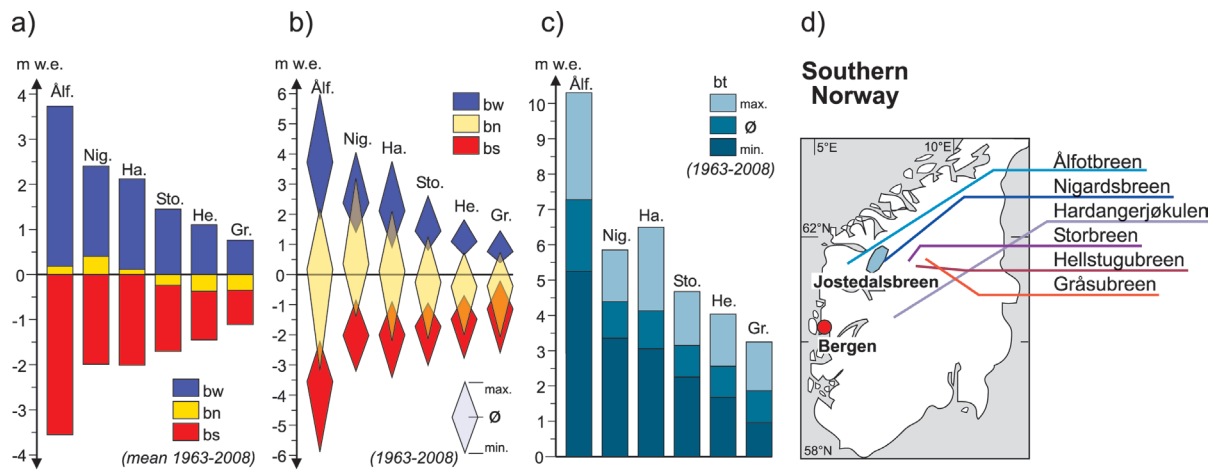
This study of maritime glaciers in southern Norway focuses in particular on Jostedalbreen and its outlets. The mass-balance series of Nigardsbreen (Fig. 6) is also representative for the whole ice cap (cf. WINKLER et al. 2009). Length-change measurements were performed at several outlets (ANDREASSEN et al. 2005; cf. Fig. 7). The best correlation with the glacier variations of Jostedalbreen has previously been achieved with meteorological data from Bergen (LIESTØL 1967; NESJE 2005; NORDLI et al. 2005). Differences between length changes of individual outlets of Jostedalbreen are related to differences in frontal time lag dependent on glacier tongue geometry, glacier size etc. (NESJE 1989; WINKLER 1996; OERLEMANS 2007). Steep and short outlets react fast and are more sensitive to changes in the mass balance than oth-

ers. Due to its continuous annual length variation record, Briksdalsbreen is chosen as an example here, whereas the other short outlets showed very similar patterns of length changes during the 20th century (Fig. 7b; cf. WINKLER 1996). These highly sensitive reacting outlets of Jostedalbreen underwent two contrasting periods of strong advance followed by rapid frontal retreat during the past 20 years (WINKLER et al. 2009). Interpretation of this ‘extreme’ behaviour deserves special attention.

3 Length variations and mass balance during the past 20 years

An approximately 30-year period of stationary or slightly advancing frontal positions at the short outlets of Jostedalbreen ended in the late 1980s. Subsequently, these glaciers experienced a significant advance during the 1990s (Fig. 8). The cause of this advance was a considerable ice mass gain, mainly achieved during a period of seven consecutive positive budget years from 1989 to 1996 (Figs. 3, 6a). The cumulative net mass balance during that period was +10.4 m w.e. (water equivalent) at Nigardsbreen (WINKLER et al. 2009). Meteorological data from Bergen reveal a concurrent trend of increased winter precipitation (Tab. 2) corresponding to the mass increase and above-average winter balances (ANDREASSEN et al. 2005; CHINN et al. 2005; NESJE et al. 2008a). A high correlation between winter balances and both AO (Arctic Oscillation)- and NAO (North Atlantic Oscillation)-indices indicates high cyclonic activity and strong zonal circulation with predominantly westerly airflow whilst the mass gain took place (POHJOLA and ROGERS 1997; NESJE et al. 2000; RASMUSSEN and ANDREASSEN 2005). There was neither a similar increase in ice mass, nor an advance recorded at the continental glaciers in southern Norway (WINKLER 2002; ANDREASSEN et al. 2005; cf. Figs. 2, 3).

At the end of 1990s, the short outlets of Jostedalbreen entered a few years’ transitional phase with stationary glacier fronts (Fig. 7a). With minor local deviations, they started to retreat around the year 2000, rapidly accelerating towards the most recent years. The retreat at some glacier tongues led to partial disintegration (Fig. 9). It added up to distances exceeding the preceding advance at many of the short outlets. Therefore, they presently occupy positions well inside the 1980/90-ice limit. The longer outlets did join this most recent retreat with a delay of several years. Until now, they have not



Abbreviations

bn: Net balance	max.: Maximum	Ålf.: Alfotbreen	He.: Hellstugubreen
bs: Summer balance	min.: Minimum	Nig.: Nigardsbreen	Gr.: Gråsubreen
bt: Mass turnover	Ø: Mean	Ha.: Hardangerjøkulen	
bw: Winter balance		Sto.: Storbreen	w.e.: water equivalent

Fig. 1: Mass-balance characteristics of six selected glaciers in southern Norway. (a) Means of seasonal and net mass-balance values (for the period 1963–2008), (b) range of minimums, means, and maximums of seasonal and net mass-balance values (1963–2008), (c) maximum, mean, and minimum mass turnover (1963–2008), and (d) location map of investigated glaciers (raw data: NVE [Norges Vassdrags- og Energidirektoratet]; modified after WINKLER 2009)

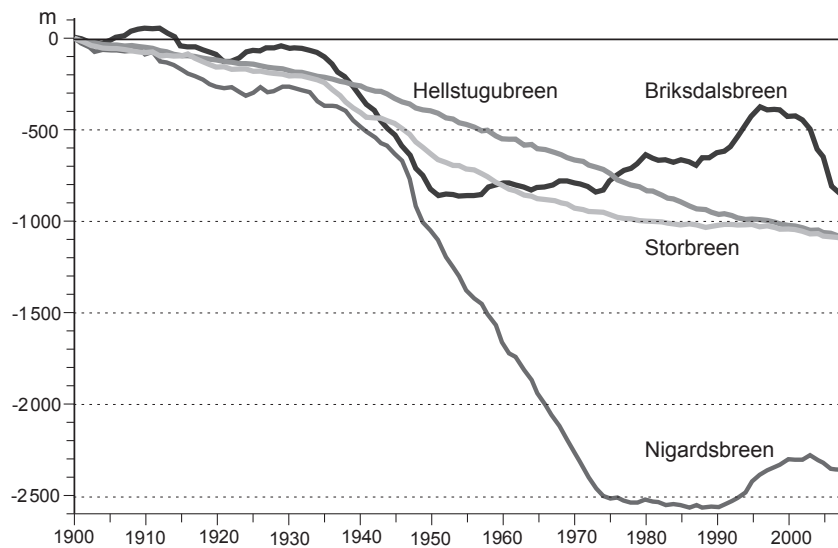


Fig. 2: Comparison of length changes (cumulative data) at Nigardsbreen, Briksdalsbreen (both Jostedalbreen, maritime southern Norway), Storbreen, and Hellstugubreen (both Jotunheimen; raw data: NVE)

shown a comparable, massive retreat (WINKLER et al. 2009). The fact that maritime glaciers in southern Norway now follow the ‘Global Trend’ (IPCC 2007; ZEMP et al. 2008), after receiving considerable attention as exceptions just a few years ago, needs to be explained more carefully.

4 Cause of the most recent length changes – a hypothesis

According to the net mass-balance data from Nigardsbreen, there was a cumulative net mass loss of c. 0.5 m w.e. from 2000 to 2008 (KJØLLMOEN

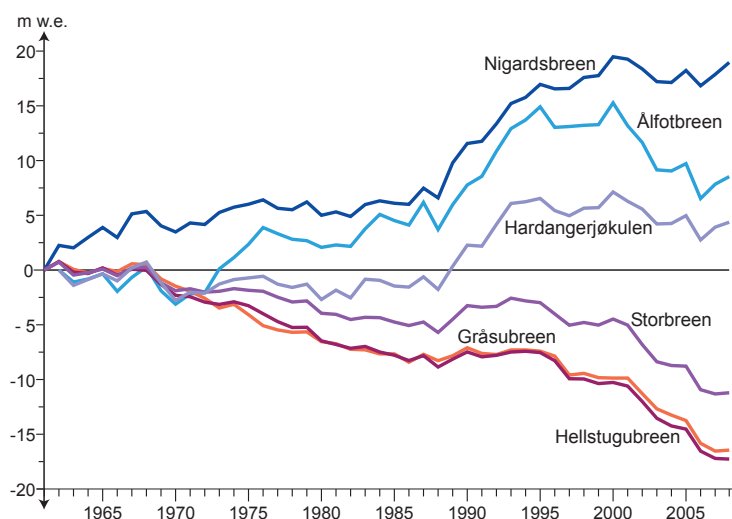


Fig. 3: Net mass balances (cumulative data) of the glaciers from figure 1 (raw data: NVE)

Table 1: Correlation (linear regression after Pearson) of (a) summer and (b) winter balances (annual data) of the six glaciers from figure 4. Despite the inherent variability in these annual data records, correlation is predominantly very positive (raw data: NVE).

(a)

(r) bs - bs	Nigardsbreen	Hardangerjøkulen	Storbreen	Hellstugubreen	Gråsubreen
Ålfotbreen	0.70	0.70	0.75	0.71	0.64
Nigardsbreen		0.90	0.86	0.85	0.73
Hardangerjøkulen			0.93	0.92	0.80
Storbreen				0.94	0.86
Hellstugubreen					0.88

(b)

(r) bw - bw	Nigardsbreen	Hardangerjøkulen	Storbreen	Hellstugubreen	Gråsubreen
Ålfotbreen	0.86	0.86	0.84	0.76	0.57
Nigardsbreen		0.88	0.90	0.83	0.70
Hardangerjøkulen			0.82	0.75	0.52
Storbreen				0.91	0.77
Hellstugubreen					0.85

2009; WINKLER et al. 2009). The length variations during the most recent retreat at all the short outlets seem not to be proportional to this net mass-balance record, especially if compared to the magnitude of the mass gain between 1988 and 2000 and its related advance (cf. Figs. 2, 3, 7; Tab. 6). Furthermore, stationary glacier fronts were monitored as early as 1997, and the retreat was already manifested in 2000 at most of the short outlets (Fig. 7a). According to previously empirically calculated terminus reaction times at those glaciers, varying between 3 and 4 years (NESJE 1989, 2005; WINKLER 1996), the retreat should have started later, i.e. after c. 2004. Accordingly, the

theoretically modelled response time of 5 years for Briksdalsbreen (OERLEMANS 2007) corresponded fairly well with the real length change data only prior to c. 1996. The close link between the net mass-balance data record and length variations evident since the early 1960s when mass balance measurements at Nigardsbreen started cannot be detected after 2000. This phenomenon is new at Jostedalbreen, has not been reported earlier, and is as yet not fully understood (see discussion).

Winter precipitation remained slightly above average during the past 10 years (WINKLER et al. 2009; Tab. 2). A decrease in winter snow accumulation can,

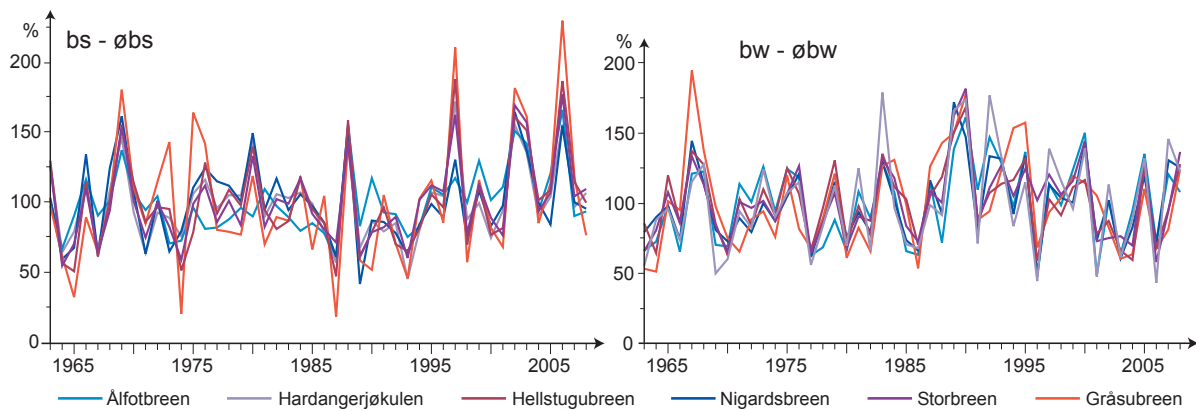


Fig. 4: Annual deviation of (a) summer and (b) winter balances from the individual 1963–2008 means (set as 100 %) of the glaciers from figure 1 (cf. Tab. 1; raw data: NVE)

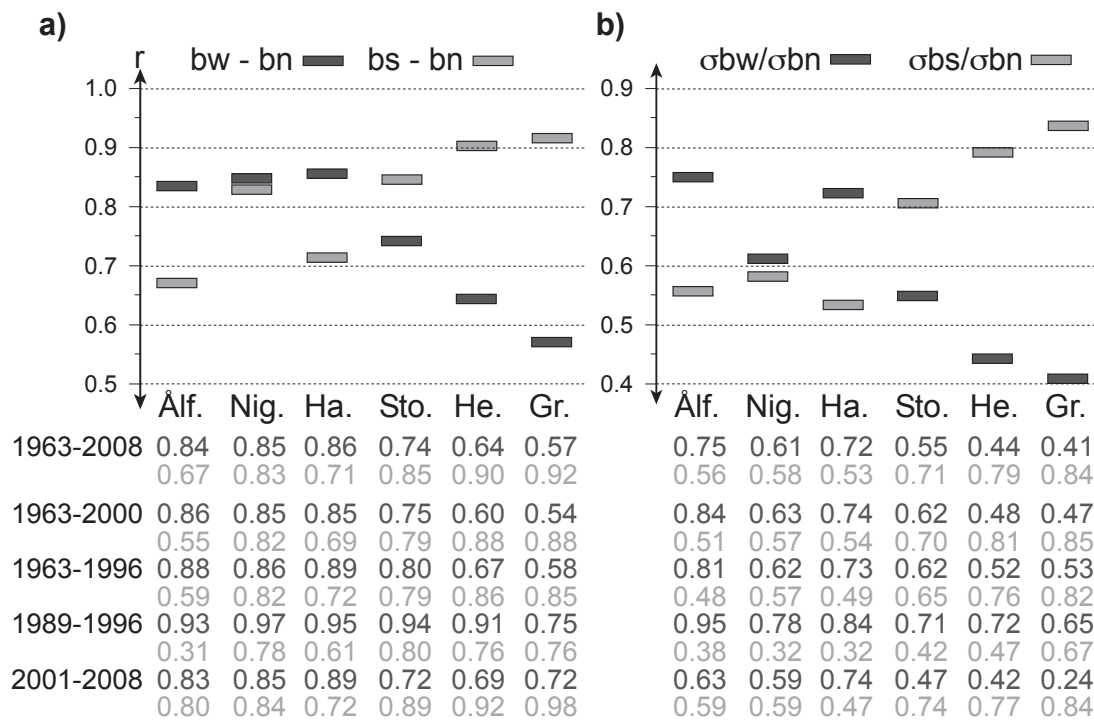


Fig. 5: (a) Correlation (linear regression after Pearson) of seasonal balances with net balance (annual data) and (b) relationship between related standard deviations of the means for the period 1963–2008 for the glacier from figure 1. The corresponding data for other selected periods are given for comparison. For detailed discussion of these relations/parameters see e.g. NESJE et al. 2000; RASMUSSEN and CONWAY 2001; WINKLER 2002; ANDREASSEN et al. 2005 (raw data: NVE)

therefore, be ruled out as a cause of the retreat. The most prominent meteorological signal is a rise of air temperature during the second half of the ablation period since the late 1990s (cf. WINKLER et al. 2009; Fig. 10). In fact, monthly means were up to 2.0 °C above the normal for 1961–1990 (Tab. 3). Already in the transition period, air temperatures were considerably higher in August and September (c. 1.5 °C). This corresponds to stationary glacier tongues at

some of the short outlets. But whereas the rise in (late) summer air temperatures clearly correlates and explains the length changes, those length changes still conflict with the net mass-balance data.

In theory, each glacier tongue should respond with a specific frontal time lag (here referred to as ‘terminus reaction time’) to any deviation from a steady-state mass flux (Fig. 11). In the present situation, this dynamic response seems obviously ‘disturbed’ as

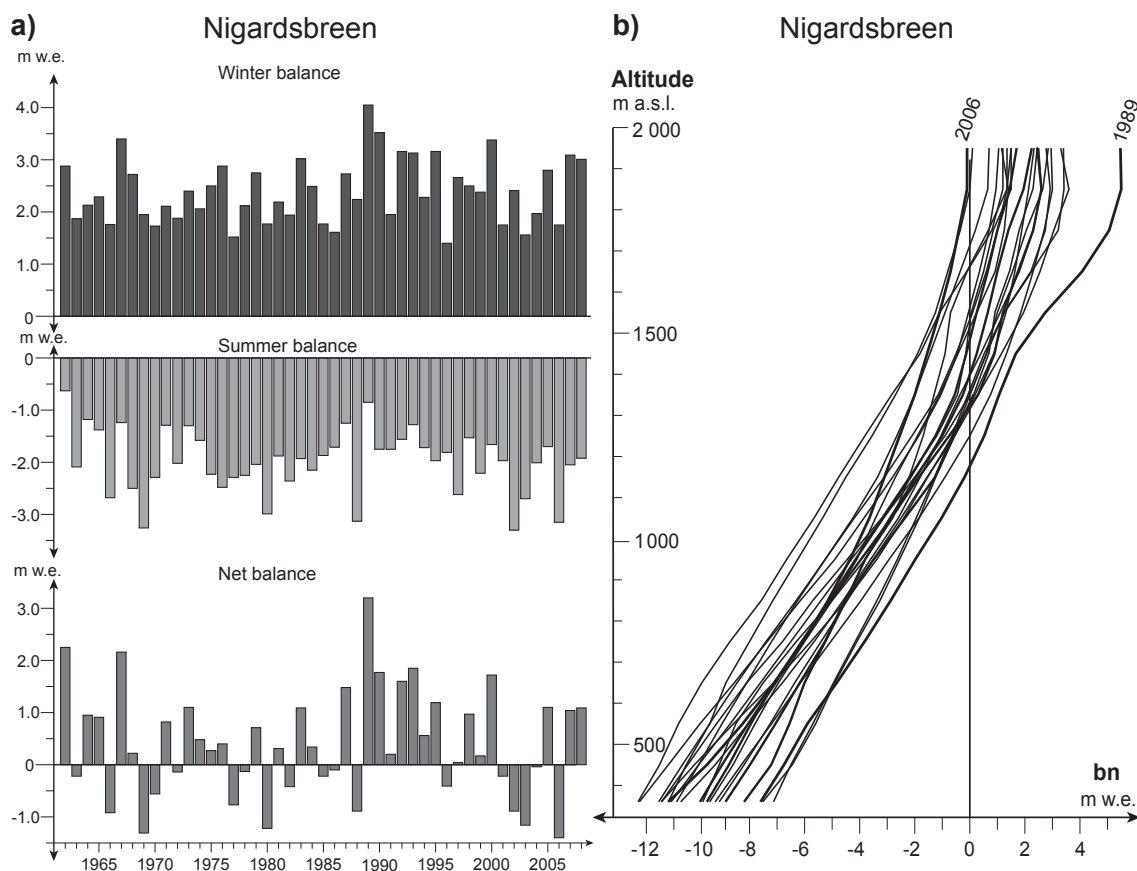


Fig. 6: (a) Mass-balance data for Nigardsbreen and (b) net mass-balance gradients for Nigardsbreen during the period 1987–2008, both showing considerable annual variations. 1989 was the year with the most positive, 2006 with the most negative net balance (data: NVE; modified after WINKLER 2009)

length variations since c. 1997 only partially reflect the net mass-balance changes (Fig. 12). The combination of steep, fast-reacting outlets with a maritime glaciological regime with high mass turnover and steep mass-balance gradients make these glaciers extremely sensitive and complex in their response to climate changes (WINKLER 2009). One result is considerable seasonal length variations. Except in years with rapidly advancing glacier fronts, summer meltback always causes reasonable seasonal retreat of the low-lying glacier fronts (WINKLER 2008, 2009). If summer meltback is enhanced due to extremely high summer air temperatures and extraordinary ablation rates, this will affect the glacier tongue immediately without any frontal time lag (Fig. 11). Furthermore, this reaction might be largely independent of the net mass-balance situation of the glacier as a whole. For example, increasing or decreasing winter snow accumulation will primarily be effective in the accumulation area of the glacier and, therefore, determined by the triggered changes of the mass flux show its

influence on the glacier terminus (with the specific time lag). But even in the status of a 'normal' or even slightly enhanced mass flux due to preceding balanced or slightly positive budget years, the reaction of the terminus to the mass flux can be disturbed by extraordinary summer meltback. Thus, a high annual retreat might be measured despite a lack of a related expected signal in the net balance data.

The steep outlets of Jostedalbreen are rare examples of significant changes in terminus reaction times. Although separate terminus reaction times related to precipitation and air temperature have previously been suggested (SALINGER et al. 1983), such suggestions have not been pursued in the attempts to calculate response times of glaciers on a theoretical level in combination with modelling (JÓHANNESSEN et al. 1989; LEYSINGER VIELI and GUDMUNDSSON 2004; HOOKE 2005; MARSHALL 2006; OERLEMANS 2007). In the case presented here, individual extents related to different conditions during the most recent advance and retreat periods have to be applied.

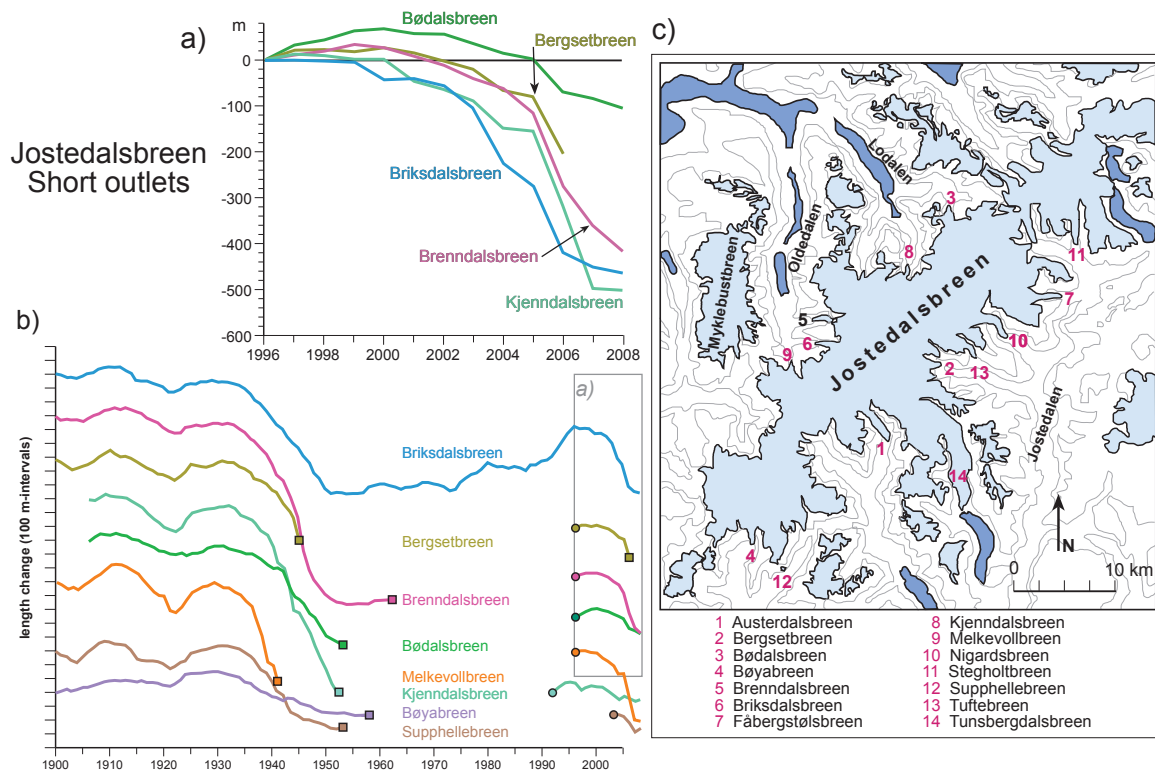


Fig. 7: (a) Most recent length variations of selected short outlets of Jostedalsgreen. Due to morphological changes of the glacier tongue the series at Bergsetbreen stopped in 2006 (cf. WINKLER et al. 2009). (b) Length variations at short outlets of Jostedalsgreen. Except for Briksdalsbreen, all measurements stopped around 1950. Except for Melkevollbreen, the measurements resumed in the 1990s (starting point not in scale to retreat in intermittent period). (c) Location map of Jostedalsgreen and its outlets (raw data: NVE; S. WINKLER)

As long as winter precipitation is the predominant climatological parameter, the glacier tongue will respond dynamically to changes of the mass flux and the previously confirmed terminus reaction time (e.g. 3 to 4 years at Briksdalsbreen) will fit perfectly. If excessive ablation caused by extremely high summer air temperatures adds to the mass loss at the glacier tongue, terminus reaction times will drop to

zero and the glacier front will react instantaneously to the weather conditions during the ablation season. This strong influence of additional enhanced meltback disturbing the pure dynamic response to changes of the mass flux is a new finding. As to our knowledge, this is not yet implemented in theoretical models and related studies on the response times of glaciers.

Table 2: Deviation of monthly winter precipitation from the 1961–90 normals for Bergen during the past 20 years, calculated as means for three periods representing advance, transition and retreat at the short outlets (raw data: DNMI [Det Norske Meteorologiske Institutt]/Met.no).

Phase:	I "Advance" (1989–1995)	I/II "Transition" (1996–2000)	II "Retreat" (2001–2008)	Normal (1961/1990)
Σ precipitation				
October	166 mm	318 mm	236 mm	271 mm
November	217 mm	197 mm	328 mm	259 mm
December	341 mm	232 mm	288 mm	235 mm
January	334 mm	219 mm	289 mm	190 mm
February	234 mm	329 mm	182 mm	157 mm
March	301 mm	210 mm	155 mm	170 mm
April	165 mm	124 mm	145 mm	114 mm

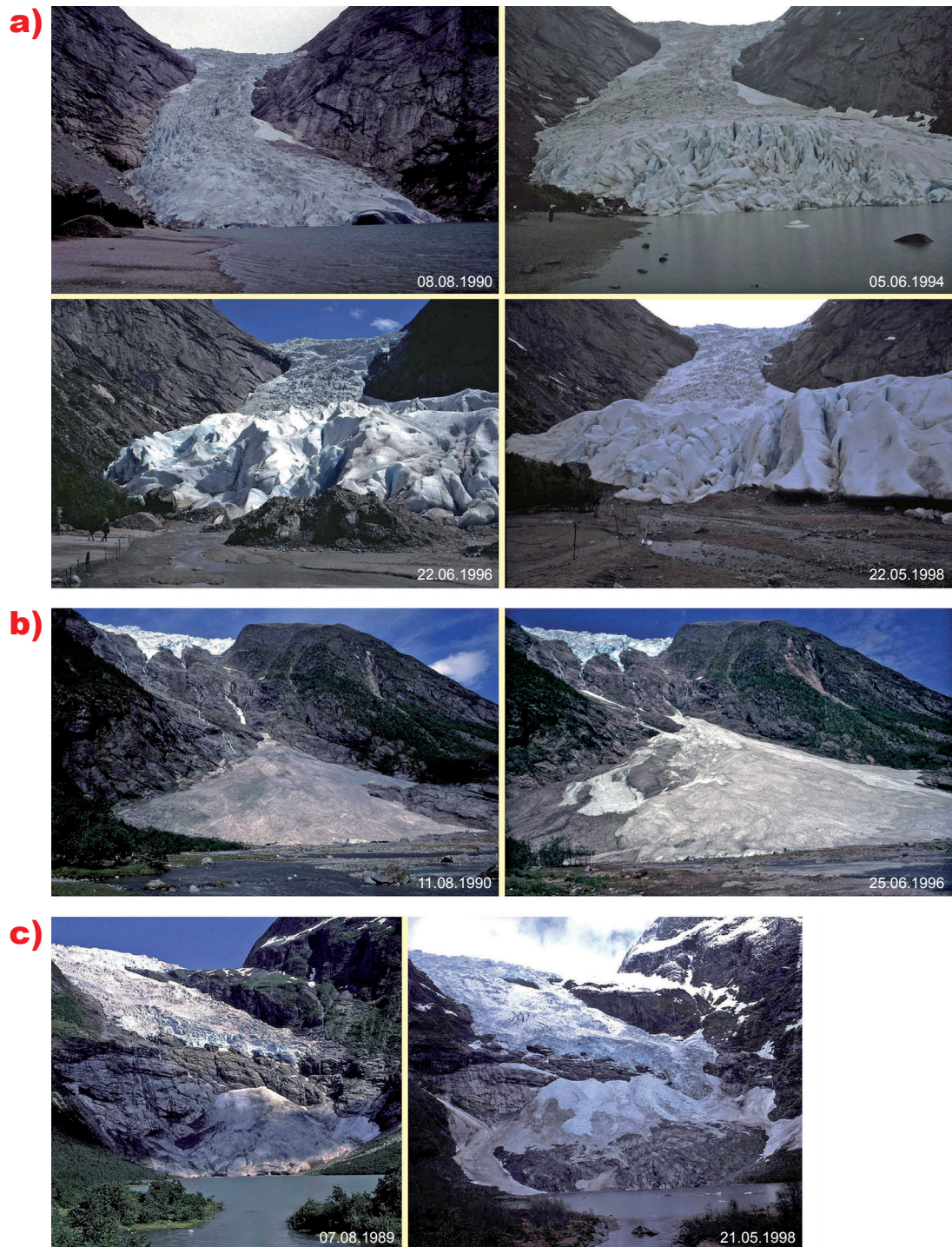


Fig. 8: Visual comparison of morphological changes at the glacier tongues of (a) Briksdalsbreen, (b) Supphellebreen, and (c) Bøyabreen during the 1990s advance (all photos © by S. WINKLER; complete photo series of 12 outlets of Jostedalsbreen are available at: http://www.geographie.uni-wuerzburg.de/arbeitsbereiche/physische_geographie/weitere_forschungsarbeiten/norglamo)

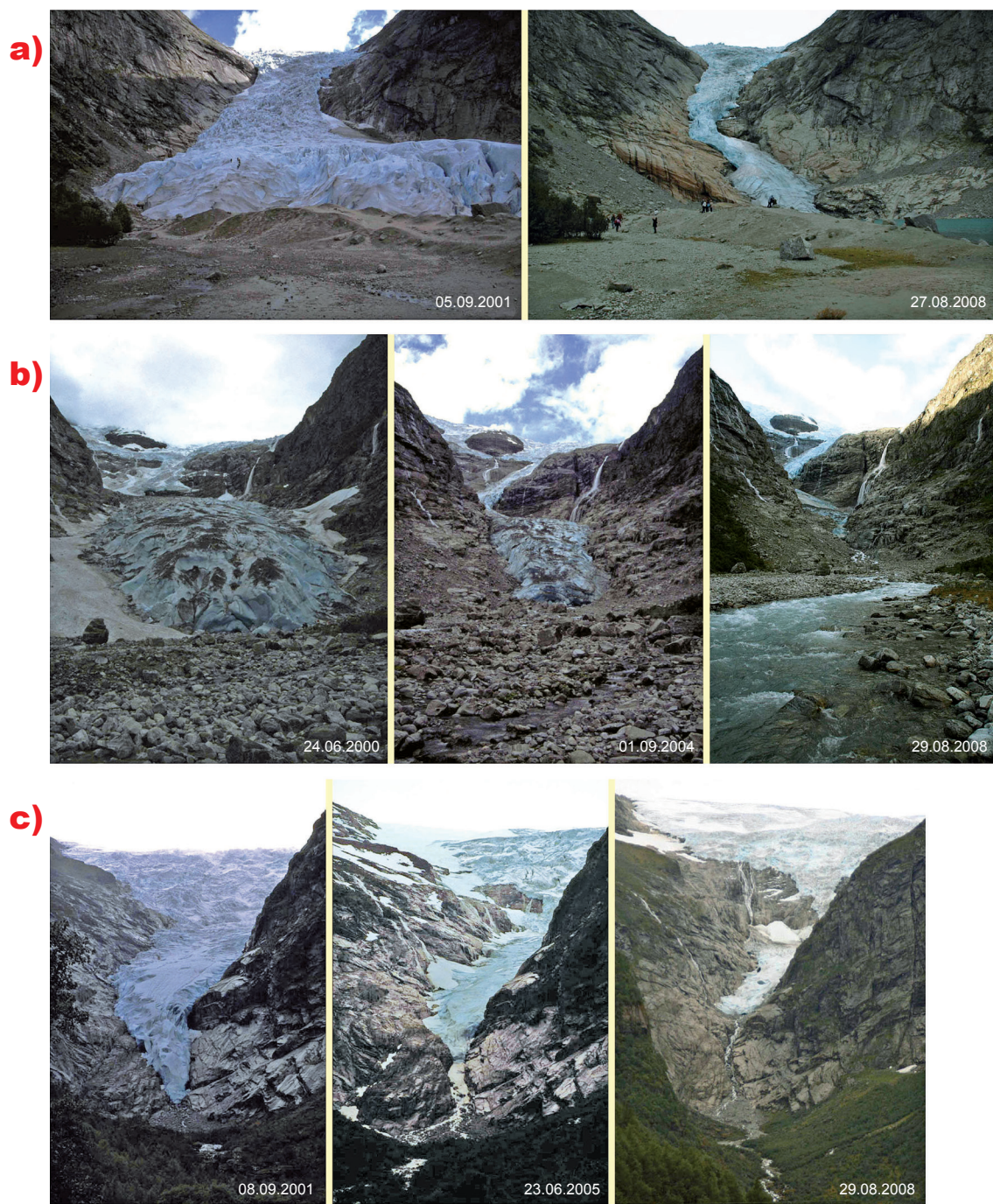


Fig. 9: Visual comparison of morphological changes at the glacier tongues of (a) Briksdalsbreen, (b) Kjenndalsbreen, and (c) Melkevollbreen (all photos © by S. WINKLER)

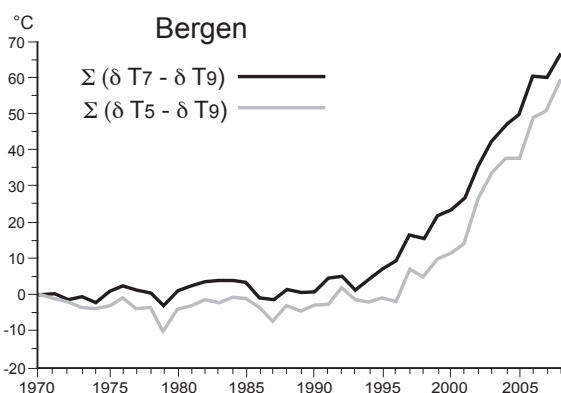


Fig. 10: Cumulative deviations of summer air temperatures for Bergen (annual sum of monthly deviations May to September and July to September) from the related 1961–90 normals (raw data: DNMI/Met.no)

We should mention one methodological problem here. Due to accessibility and other technical reasons the altitudinal values of the net mass balance for the lowermost 200–300 m of the glacier surface of Nigardsbreen usually are extrapolated (KJØLLMOEN 2008). In years with high summer ablation ratios, the conventional data might therefore to a certain degree underestimate the net mass loss at the lowermost tongue (WINKLER et al. 2009). Due to the relative small percentage of glacier area and volume located at this low altitude, the degree of uncertainty seems to be acceptable in the light of the total glacier volume. However, especially for the narrow and steep tongue of the short outlets, the consequences for to explain the length changes cannot be overseen. On the other hand, those potential methodological problems do not fully explain the present situation, as prior to 2000 they seem not to have had any considerable impact on the relationship between net mass-balance and length-change data. Furthermore, local influences can most likely be ruled out due to the parallel trend occurring at all short outlets of Jostedalbreen (Figs. 7a, 9). Even if, for example,

calving over a small proglacial lake influenced the fast retreat of Briksdalsbreen and is assumed as responsible for the non-reproducibility in an up-to-date simulation (LAUMANN and NESJE 2009), this explanation cannot be applied at other outlets with a comparable strong retreat.

5 Changes of the glaciological regime?

There are clear indications that the glaciological regime was partially modified after 2000. Substantial changes occurred with the correlation of the net mass-balance parameters to length variations (Tab. 4). The correlation of net mass balance to length changes dropped significant during the most recent retreat since 2000 indicating that the previous close coupling of net mass-balance data record and length variations cannot longer be applied unaltered to explain the frontal behaviour. Furthermore, it can be detected that the consideration of terminus reaction times now leads to less significant results. This means that length changes at the terminus are now less influenced by the mass transfer in favour of an immediate response to (excessive) summer ablation. It also explains why (not delayed) summer balance data experiences a high correlation with length changes ($r = 0.97$) during the last few years (WINKLER et al. 2009) despite of its methodological uncertainties and partial dependency on the preceding winter balance. The negative correlation of net mass balance with frontal variations during the transition period (meaning simultaneous mass increase and frontal retreat) seems striking.

Comparable changes between long-term means and the most recent retreat phase take place between selected meteorological parameters and length variations (Tab. 5). The high correlation of winter temperatures with length changes, easily explained by the impact of winter precipitation

Table 3: Deviation of monthly summer air temperatures from the 1961–90 normals for Bergen, calculations corresponding to table 2 (raw data: DNMI/Met.no).

Phase:	I "Advance" (1989–1995)	I/II "Transition" (1996–2000)	II "Retreat" (2001–2008)	Normal (1961/1990)
Ø air temperature				
May	10.4 °C	10.0 °C	10.7 °C	10.5 °C
June	12.9 °C	13.0 °C	13.7 °C	13.3 °C
July	14.7 °C	14.5 °C	16.3 °C	14.3 °C
August	14.1 °C	15.6 °C	16.1 °C	14.1 °C
September	11.6 °C	12.7 °C	12.7 °C	11.2 °C

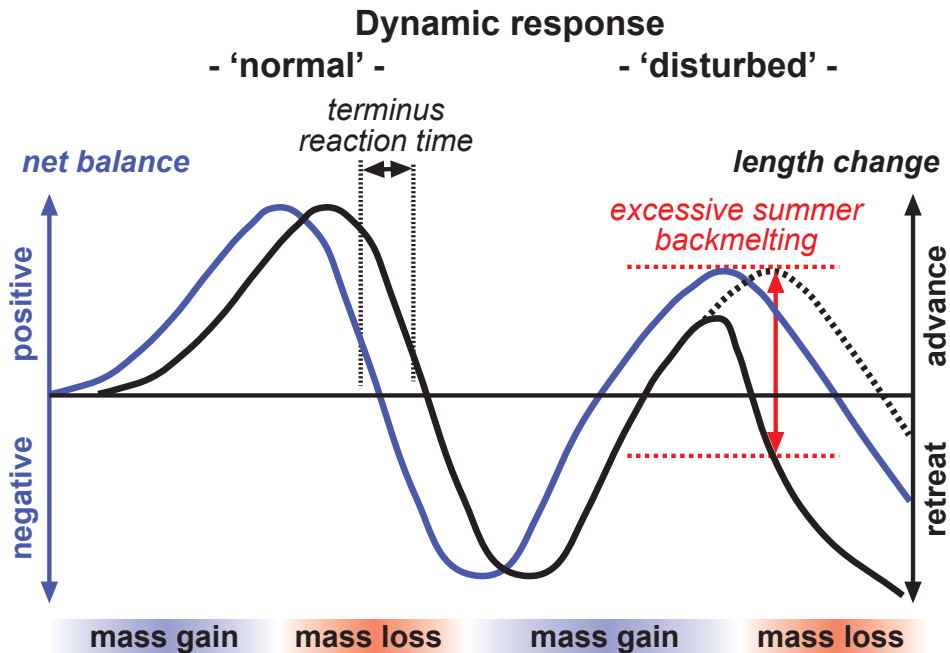


Fig. 11: Schematic visualisation of the response of a glacier tongue to mass flux fluctuations (cf. text)

on the mass balance (mild winter = high snow accumulation), has dropped significantly during the most recent years. By contrast, the results for summer air temperature parameters (positive departures correspond to negative length changes) have changed as expected. If compared to the values for the preceding period, it becomes obvious that summer air temperature nowadays has a higher impact on length changes than before.

This analysis reveals substantial changes in the relationships and interrelation within the glaciological regime during the past 20 years. The partially surprising results give a clear warning to the common procedure of averaging long-term data series of glaciological and meteorological parameters as input for existing models. These inputs must not automatically be considered as constant. Temporally and spatially differentiated, high-resolution data and multiple-phase regression seem to be appropriate strategies in the context of significant weather regime changes. However, this refers merely to length variation data, as no distinct regime change was detected in the mass-balance data (Fig. 5). Only during the short period from 2001 to 2006, a few coefficients showed some moderate departures, e.g. at Ålftobreen (bs–bn: $r = 0.66$ for 2001–2006; $r = 0.80$ for 2001–2008) or Nigardsbreen (bw–bn: $r = 0.71$ for 2001–2006; $r = 0.85$ for 2001–2008).

6 Annual air temperatures indicative for length changes?

In some studies, glacier length variation data is used to calculate the air temperature rise during the 20th century and deduce anthropogenic influences (e.g. OERLEMANS 1994, 2005). Detailed glaciological and meteorological data from southern Norway along with general considerations (cf. WINKLER 2002) raise, however, major concerns with that practice. Firstly, annual air temperature data are normally related to calendar years. By contrast, glacier mass-balance data are calculated for glacier budget years (1st October

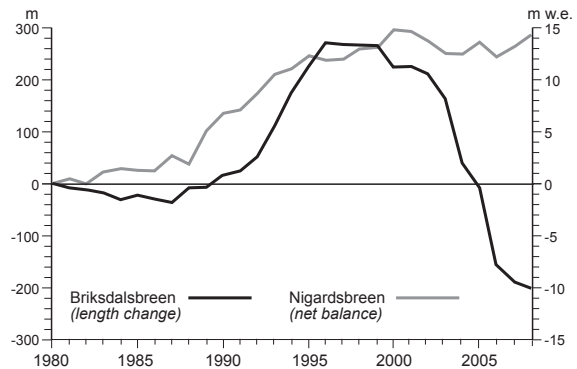


Fig. 12: Comparison of length variations of Briksdalsbreen with the cumulative net mass-balance series of Nigardsbreen (raw data: NVE)

Table 4: Correlation (linear regression after Pearson) of different net mass-balance parameters for Nigardsbreen with length variations at Briksdalsbreen (cumulative data series). The three multi-year phases correspond to those in table 2. For net balance, length changes with different terminus reaction times of 3, 4, and 5 years [t_r : 3a, 4a, 5a] are included (raw data: NVE; in parts modified after Winkler et al. 2009).

(r) length change Briksdalsbreen:	Phase I “Advance” (1989–1995)	Phase I/II “Transition” (1996–2000)	Phase II “Retreat” (2001–2008)	Period 1963–2007	Period 1963–2000	Period 1963–1996
Net balance	0.96	-0.94	0.50	0.77	0.93	0.89
Net balance (t_r : 3 a)	0.94	-0.93	n/a	0.70*	0.79	0.92
Net balance (t_r : 4 a)	0.85	-0.96	n/a	0.64*	0.88	0.94
Net balance (t_r : 5 a)	0.47	-0.92	n/a	0.57*	0.64	0.92

(* - period ends 2002 to 2004 according to particular terminus response time)

Table 5: Correlation (linear regression after Pearson) of different air temperature parameters (sum of deviation of monthly air temperature means from 1961–90 normals) for Bergen with length variations at Briksdalsbreen (cumulative data series). The three multi-year phases correspond to those in table 2. For the sum of May–September, length changes with different terminus response times of 3, 4, 5 years [t_r : 3a, 4a, 5a] are included (raw data: DNMI/Met.no, NVE; in parts modified from Winkler et al. 2009).

(r) length change Briksdalsbreen:	Phase I “Advance” (1989–1995)	Phase I/II “Transition” (1996–2000)	Phase II “Retreat” (2001–2008)	Period 1963–2007	Period 1963–2000	Period 1963–1996
$\Sigma \delta(T \text{ Oct–Apr})$	0.76	-0.91	-0.91	0.60	0.90	0.86
$\Sigma \delta(T \text{ Jun–Sep})$	0.63	-0.70	-0.96	0.27	0.81	0.73
$\Sigma \delta(T \text{ May–Sep})$	0.37	-0.65	-0.93	0.14	0.55	0.09
$\Sigma \delta(T \text{ May–Sep})$ (t_r : 3a)	0.66	-0.91	n/a	-0.06*	0.37	0.05
$\Sigma \delta(T \text{ May–Sep})$ (t_r : 4a)	0.78	-0.72	n/a	-0.10*	0.28	0.07
$\Sigma \delta(T \text{ May–Sep})$ (t_r : 5a)	0.61	-0.83	n/a	-0.11*	0.17	0.08

(* - period ends 2002 to 2004 according to particular terminus response time)

to 30th September). Annual length changes are regularly measured in late summer and roughly correspond to budget years. When comparing ‘annual’ air temperatures for Bergen calculated for both calendar years and budget years, differences of up to $\pm 1^\circ\text{C}$ emerged (Fig. 13a). The average deviation for the period 1900–2000 was $\pm 0.28^\circ\text{C}$ and increased towards the most recent years (Fig. 13b). Only a rather weak trend was derived lacking any clear pattern or conspicuous explanation. As a consequence, if meteorological parameters on an annual basis are linked to mass-balance or length variation data, they must be calculated for budget years and not for calendar years. This rather logical rule has not yet received enough attention.

There seems to be no obvious relation of net mass-balance or length change data from maritime southern Norway during the past decades to the averaged meteorological parameter ‘annual air temperature’, even if the latter one is calculated for budget years (see Tab. 6). By contrast, although annual air temperatures are above average during the most recent years with its strong frontal retreat and (minor) net mass loss, they were also above the long-term

means during the 1990s with its considerable net mass increase and advance. The latter phenomenon was due to high winter air temperatures (Fig. 13c). Relatively high winter air temperatures indicate mild and moist winter seasons with considerable snow accumulation and, therefore, favourable conditions for the glaciers. By contrast, above average summer air temperatures cause high ablation and high mass loss in summer. Positive departures of the air temperature from the long-term means during the ablation season have, therefore, a very negative impact on the glaciers. Negative departures of air temperatures e.g. during cold and dry winter seasons are less favourable for the net mass balance, and low summer air temperatures will reduce ablation in favour of a positive net balance. For southern Norway, these consequences are confirmed by empirical data e.g. for the ‘Little Ice Age’ (NESJE and DAHL 2003; NESJE et al. 2008b).

Although air temperatures have an important impact on the net mass balance and length variations at the maritime glaciers of southern Norway, they need, therefore, to be analysed in the light of seasonality. Mid-litudinal maritime glaciers experience a marked seasonal differentiation in their mass budget. The dif-

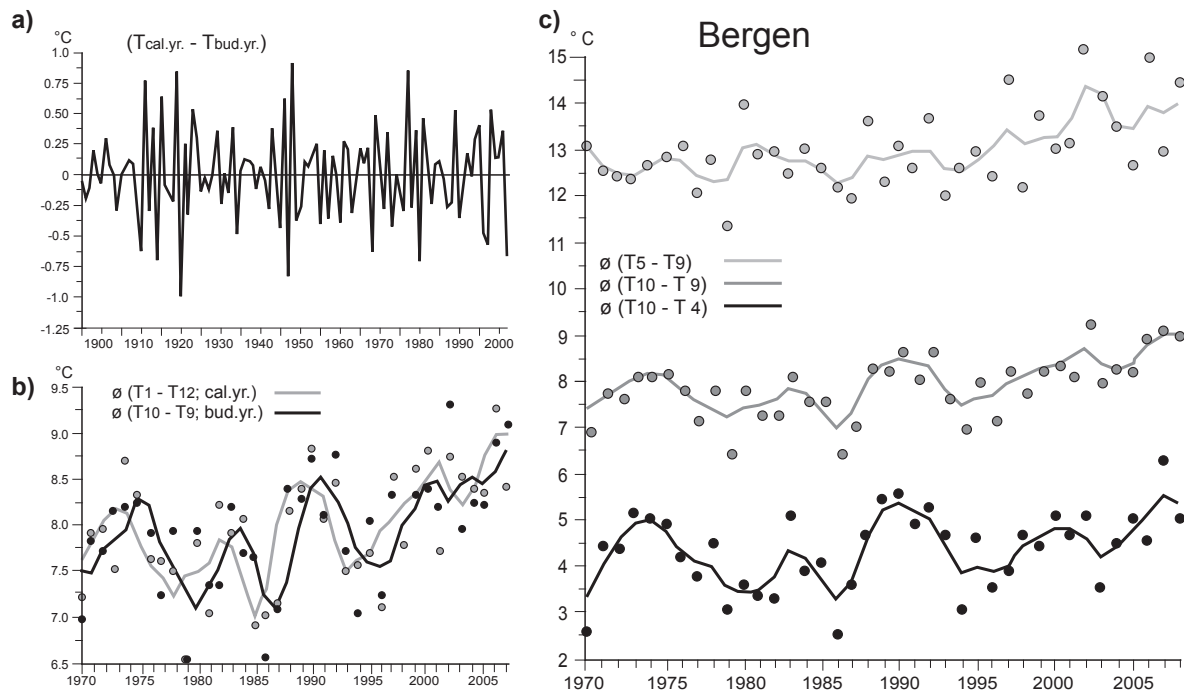


Fig. 13: (a) Difference between ‘annual air temperatures’ related to calendar and budget years, respectively, for Bergen. (b) Comparison of ‘annual air temperatures’ related to calendar and budget years, respectively, for Bergen. The solid lines are five-year Gaussian low-pass filters. (c) Comparison between winter, summer, and (budget year) annual air temperatures for Bergen. The solid lines are five-year Gaussian low-pass filters (raw data: DNMI/Met.no)

ferentiation between winter and summer balance is regarded as useful for the analysis of the influence of single climatological factors upon the mass-balance (DYURGEROV and MEIER 1999; STEINER et al. 2008). This indicates why parameters that do not include such seasonal differentiation, as for example, annual air temperature data, are poor indicators of glacier mass balances or related length variations in maritime mid-latitude environments. A successful application of this parameter would require that (a) only the climatic conditions during the ablation season determine the net mass balance and (b) only summer air temperatures show detectable departures from the long-term means. As (a) already has been disproved for southern Norway (Fig. 5), (b) is fairly unrealistic and refutable on the basis of existing data as well (Fig. 13).

As no causal link between the parameter ‘annual air temperature’ and glacier variations could be detected during the past decades in southern Norway, these maritime glaciers should be excluded from the above-mentioned studies, at least on decadal- and secular-time scales. Air temperature data need to be seasonally differentiated and combined with precipitation and eventually other energy balance variables before it might successfully be related to length changes. This recommendation might considerably complicate

the existing attempts to extract a single climatic signal from the available length change data available, but seems necessary in order to prove that, for example, ‘parallel’ trends of rising annual air temperatures and glacier retreat during the 20th century (following the ‘Little Ice Age’) are of more than statistical nature. At least for maritime mid-latitude mountain glaciers, the causal links between annual air temperature data sets (especially if they are averaged on a global scale) and length variation are still awaiting ultimate proof of linkages.

7 Conclusions and outlook

In summary, some facts about the most recent glacier variations in southern Norway need to be addressed, regarding the frequent use of data for modelling and related studies. Since 2000, length variations at the short outlets of Jostedalsglacier seem to be decoupled from the net mass-balance data series. The dynamic response of the glacier front to net balance and mass flux variations has been disturbed. Previously applicable terminus reaction times of 3 to 4 years have been replaced by an immediate response to higher summer air temperatures. Even if their de-

Table 6: Comparison between mean annual air temperatures for Bergen (calculated for budget years), net mass balance for Nigardsbreen (cumulative date), and length changes at Briksdalsbreen (cumulative data) for selected periods. This table clearly shows that there is no discernible pattern between the data series, raising serious doubts whether a causal link between length-change records and net mass balance/annual air temperatures really can be concluded for this region (raw data: DNMI/Met.no, NVE).

Period	Ø Annual air temperature (budget year) Bergen	Σ Net balance Nigardsbreen	Σ Length change Briksdalsbreen
2001–2007	8.56 °C	+0.15 m w.e.	-408 m
1996–2000	8.02 °C	+2.49 m w.e.	0 m
1989–1995	8.10 °C	+10.37 m w.e.	+230 m
1981–1988	7.53 °C	+1.71 m w.e.	-9 m
1970–1980	7.70 °C	+0.96 m w.e.	+132 m

gree of dominance underwent a slight decrease following the 1990s advance, winter balance and winter precipitation conditions are still important driving factor for the mass-balance. A way of integrating possible regime shifts into glacier models needs to be determined. This is essential as relatively short time periods experience substantial frontal advance and retreat. Because empirical explanations and models based on long-term data that previously delivered satisfactory solutions for the interpretation of the glacier variations do not work in the present situation (since 2000), they should not be applied untested for modelling future glacier variations. On the other hand, models based on measurements performed during the few years after 2000 will not necessarily be representative for glacier behaviour before 2000. That a major retreat like the one since 2000 might occur without a simultaneous net mass loss needs to be taken into account if glacier variations for periods prior to the start of mass balance monitoring are analysed.

As it is crucial to understand the response of the glacier tongues to future climate change, short-term extreme situations – rather than long-term constant developments – need to be the focus of new studies. The concept of possible regime shifts and multi-phase patterns of causal interactions between meteorological parameters and glacier length changes has to be accepted as hypothesis in future work.

Finally, the pure dynamic response of the glacier front to mass-balance changes can be disturbed at low-lying maritime mountain glaciers with high rates of summer meltback. Alteration of terminus reaction times can be used as indicator. If the terminus response is mainly driven by changes of the mass flux, a specific terminus reaction time ($t_r \geq 1$ yr.) will be in place. If enhanced ablation at the terminus crossed a specific threshold, this terminus reaction time will be replaced by an immediate response ($t_r = 0$) independent of the mass flux determined by the net mass-balance situation during the preceding

years. Whereas mass balance and dynamic response of the glacier front might be modelled with existing knowledge and available conventional mass-balance data, to quantify these surplus ablation/additional enhanced summer meltbacks might be a methodological task for the future. This could be undertaken by applying new procedures and techniques (e.g. high-resolution geodetic methods like annually repeated terrestrial laser scanning). Simultaneously, thresholds of summer air temperature specific for this region need to be found in order to respond to this relatively new development that is without analogy in the historic or recent records. As a consequence, different terminus reaction times for advance/retreat, precipitation/air temperature, or dynamic response/disturbed dynamic response have to be introduced. In the light of climate models unanimously forecasting an increase in precipitation in maritime southern Norway (BELDRING et al. 2007; HAUGEN et al. 2008; SORTEBERG and ANDERSEN 2008), all types of glacier models including precipitation as a constant input (e.g. certain energy-balance models and their derivatives) will produce results that have primarily to be regarded as less realistic. However, it will be an important question whether winter precipitation retains its strong influence during the 21st century and length variations remain decoupled from the conventional net mass-balance record, thus complicating any attempt to forecast those length changes.

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Authors

Privatdozent Dr. Stefan Winkler
Department of Geography,
University of Würzburg,
Am Hubland,
97074 Würzburg, Germany,
stefan.winkler@uni-wuerzburg.de

Professor Atle Nesje
Department of Earth Sciences,
University of Bergen,
Allégt. 41,
5007 Bergen
Norway,
atle.nesje@geo.uib.no