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Glacier fluctuations of Jostedalsbreen, western Norway, during the past 20 years: the sensitive response of maritime mountain glaciers

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Abstract: The steep outlet glaciers of Jostedalsbreen, western Norway, are good examples of sensitively reacting maritime mountain glaciers. Their changes in length, frontal position and lower tongue's morphology during the past 20 years have been well documented. At first they experienced a strong frontal advance. After AD 2000 glacier behaviour was dominated by a strong frontal retreat, in some cases causing a separation of the lowermost glacier tongue. In this paper, the glacier length changes are presented both visually and numerically, supplemented by mass balance and meteorological data. The glacier behaviour is interpreted and its causes are discussed. Whereas the factors controlling the advance during the 1990s seem clear, the interpretation of the most recent retreat still leaves some uncertainties. The actual glacier front behaviour cannot fully be related to the mass balance data. Terminus response times and relations between individual mass balance and meteorological parameters have changed. Some hypotheses are given, including disturbance of the 'normal' mass transfer and dynamical response of the glacier front because of excessive ablation on the lowermost glacier tongues and summer back melting. These findings underline the sensitivity of maritime glaciers to climate changes. The empirical findings need to be taken into account in the interpretation of recent glacier length changes and their future modelling.

Key words: Glacier variations, climate change, western Norway, glacier length change, mass balance, terminus response time, Jostedalsbreen, outlet glaciers, mountain glaciers.

Introduction

Mountain glaciers are widely acknowledged as high-resolution indicators of short-, medium- and long-term climate changes (Oeschger and Langway, 1989; Nesje and Dahl, 2000; Oerlemans, 2005; Barry, 2006; Intergovernmental Panel on Climate Change (IPCC), 2007). In the context of discussing the causes and consequence of the present climate change, mountain glaciers have received increasing attention. Variations in glacier mass, area, length and frontal position have important consequences for freshwater resources, hydroelectrical power generation, natural risk management and sustainable development in mountain regions (Guisan *et al.*, 1995; Jeannert *et al.*, 2003; Bamber and Payne, 2004; Huber *et al.*, 2005). Owing to their high mass turnover, maritime mountain glaciers react sensitively to changes in the predominant weather and climate conditions. Their glaciological regime, ie, the specific interactions and influences of factors within the system of mass balance, is different from those of glaciers in different climatic settings (Nesje and Dahl, 2000; Winkler, 2002, 2009). Therefore, there is need for detailed understanding of the response of mountain glaciers to past, present and future climate change. The focus of this study is exclusively upon maritime mountain glaciers of the middle latitudes.

Glaciers in southern Norway have been studied in detail for several decades. Jostedalsbreen ice cap and its outlets (Figure 1, Table 1) received considerable attention during the 1990s because

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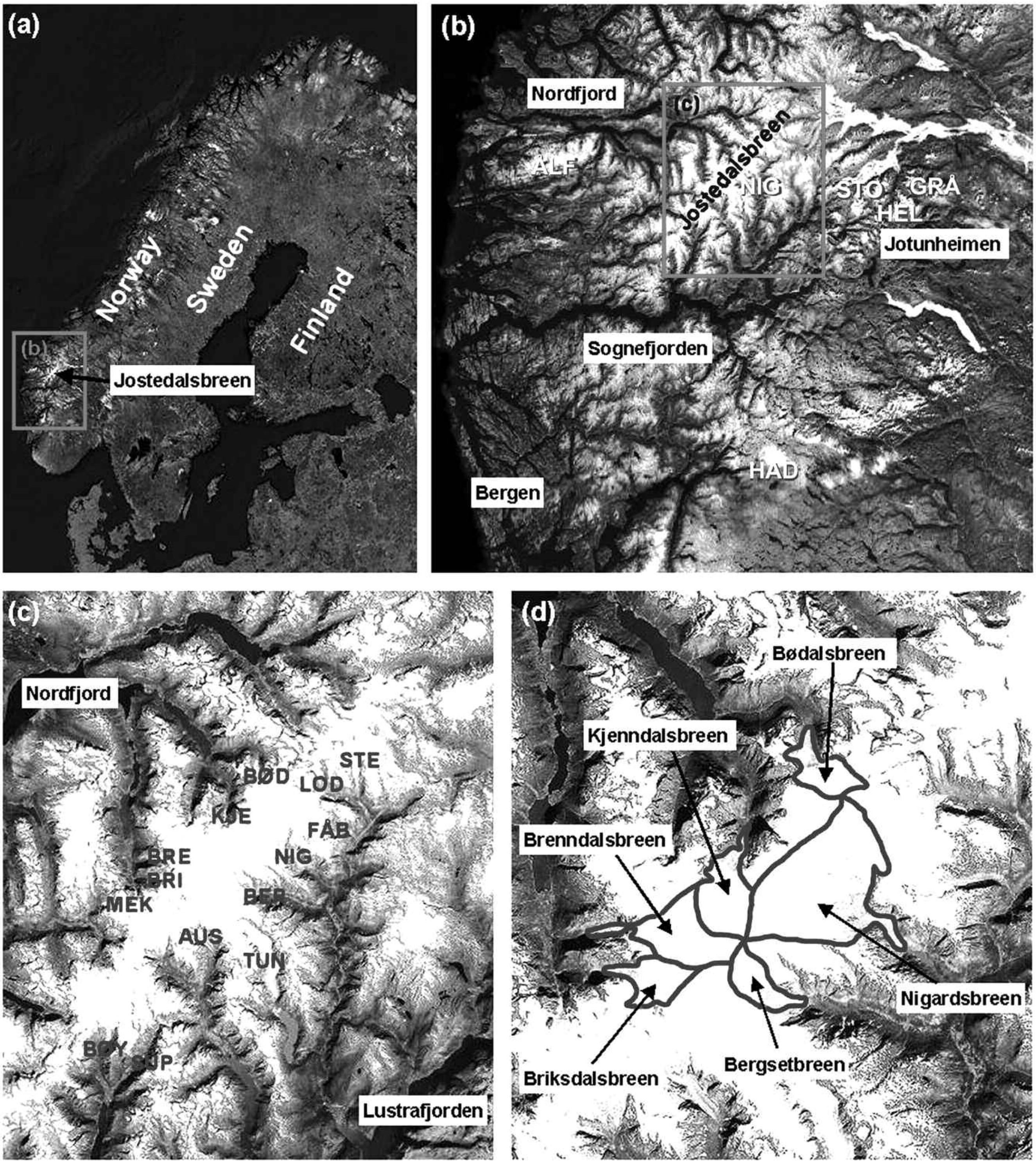

Figure 1 (a) Map of Norway/northern Europe with location of Jostedalsbreen. (b) Map of southern Norway. The glaciers with long mass balance series are indicated (ÅLF, Ålfotbreen; NIG, Nigardsbreen; HAD, Hardangerjøkulen/Rembesdalsskåka; STO, Storbreen; HEL, Hellstugubreen; GRÅ, Gråsubreen). (c) Map of Jostedalsbreen. The most important outlets glaciers are indicated (AUS, Austerdalsbreen; BER, Bergsetbreen; BØD, Bødalsbreen; BØY, Bøyabreen; BRE, Brenndalsbreen; BRI, Briksdalsbreen; FÅB, Fåbergstølsbreen; KJE, Kjenndalsbreen; LOD, Lodalsbreen; MEK, Melkevollbreen; NIG, Nigardsbreen; STE, Stegholtbreen; SUP, Supphellebreen; TUN, Tunsbergdalsbreen). (d) Map of the central part of Jostedalsbreen showing the glacier area of the studied outlet glaciers (all maps modified after http://www.googlemaps.com)

of a substantial ice mass increase, resulting in a strong frontal advance (Winkler *et al.*, 1997; Andreassen *et al.*, 2005). This glacier advance was exceptional in a global context, with only a few other regions (eg, New Zealand) experiencing comparable advances in the same period (Chinn *et al.*, 2005). At many outlets of Jostedalsbreen, that advance terminated around (or slightly prior to) the year 2000. Since then, most of those glaciers have experienced a major ice-marginal retreat leading, in some cases, to partial disintegration of their lower glacier tongues.

Whereas the causes of the glacier mass increase and the basic mechanisms of the related length changes during the recent advance are well known, and mainly uncontroversial, the ongoing

Table 1 Topographical data for selected outlet glaciers of Jostedalsbreen

Glacier	Area (km^2)	Length (km)	Altitude (m a.s.l.)
Nigardsbreen	48.20	9.6	350–1950
Tunsbergdalsbreen	47.69	19.1	590–1930
Austerdalsbreen	26.84	8.5	390–1920
Kjenndalsbreen	19.06	6.9	180–1960
Stegholtbreen	15.34	7.7	880–1900
Brenndalsbreen[a]	17.97	9.6	310–1960
Fåbergstølsbreen	15.00	7.0	760–1810
Bøyabreen	13.90	5.7	145–1730
Lodalsbreen	12.18	6.0	860–1960
Briksdalsbreen	11.94	6.0	350–1910
Supphellebreen	11.81	8.4	720–1730
Bergsetbreen	10.50	4.8	540–1960
Bødalsbreen	8.22	6.5	650–1990
Melkevollbreen	4.94	4.3	410–1870

[a] Annual length measurements are made at the lower glacier tongue representing a regenerated glacier.

The data are taken from Østrem *et al.* (1988); the data for the altitude of the lower glacier margin have later been modified by Winkler *et al.* (1997) and should represent the situation around AD 2000.

retreat leaves some uncertainties. The magnitude of this retreat compared with the mass budget development and the temporal scale (terminus response time) can neither be explained by established empirical-derived relationships nor by existing models. As it is important for any prediction of glacier behaviour in the near future, it is essential to discuss and find possible explanations for this most recent retreat.

The main goal of this study is to demonstrate and explain the sensitive response of the outlets from the maritime Jostedalsbreen ice cap to mass balance perturbations and short-term climate change at high temporal resolution. Following a brief resume of the established explanations for the glacier advance during the 1990s, discussion focuses on possible explanations for the glacier front response since *c*. 2000 and why relationships between glacier length changes and mass balance variations changed around the year 2000. Because of the short observation period it is, however, too early for any final solution. As most climate scenarios predict an increasing probability of extreme weather conditions (Sælthun *et al.*, 1990; IPCC, 2007; Grønås *et al.*, 2007), it is important to assess whether established ideas on the relationship between glacier length changes, mass balance and climate are wrong in general or just perturbed or altered in the present case. Furthermore, as most models use long-term average glaciological and meteorological data within their data base, it is essential to assess whether different modes of glacier response exist, necessitating multiphase, variable algorithms to be developed and applied.

Glacier length measurements and photographic monitoring of glacier front positions

Historical documents, drawings and paintings, first scientific descriptions, maps, lichenometric dating and other evidence allow a quite accurate reconstruction of the glacier front behaviour of Jostedalsbreen after the 'Little Ice Age' maximum around AD 1750 (Forbes, 1853; Grove, 1988; Bogen *et al.*, 1989; Bickerton and Matthews, 1993; Winkler, 2001; Nesje *et al.*, 2008a). The oldest photographs of glacier tongues available date from the mid 1860s and successive photographs give a good picture of the ice margins during the later part of the nineteenth century (Winkler, 1996a). J. Rekstad initiated annual glacier length measurements at Jostedalsbreen around the year 1900 (Rekstad, 1904; Fægri, 1948; Hoel and Werenskiold, 1962). Unfortunately, annual measurements stopped at a number of outlets during the 1940s and 1950s. Among those glaciers with a continuous record (Figure 2a), Briksdalsbreen is the only one representative of the short and steep outlet glaciers characterized by short terminus response times. In reaction to the recent glacier advance and inspired by a conference of the International Glaciological Society (IGS) in Fjærland in June 1996, glacier length measurements were resumed the same year at three short outlet glaciers in Nordfjord (Brenndalsbreen, Bødalsbreen, Kjenndalsbreen) and at Bergsetbreen in Jostedalen (Figure 2b). At the three glaciers in Nordfjord, twice-yearly measurements (early and late summer) were carried out to register additionally seasonal glacier-length variations (Kjøllmoen, 2008; Figure 2c).

Glacier length change is a proxy measure of glacier area change and therefore useful for the analysis of the climatologic causes of glacier variations in periods or at locations where no direct glacier mass balance data are available. The distance from a fixed point (cairn, bolt or painted mark) to the glacier margin in a pre-defined direction preferably 'close' to the central flow line is measured at the end of summer. This measurement is repeated annually (preferably during the same week), and the length change is calculated. Single measurements might, however, be influenced by the local topography of the glacier snout, depending on where the fixed line hits the glacier margin. Calculated length change from single years that deviate from multiyear trends must therefore be evaluated with care and cumulative data are preferred.

Visual monitoring of the lower glacier tongues provides valuable additional information. J. Rekstad took photos at most of the glaciers during the start of his annual measurements (Rekstad, 1912). For example, while the frontal measurements at Bergsetbreen had not yet given an indication of the onset of a short advance during the first decade of the twentieth century, the contemporary photos showed a significant thickening of the ice fall/upper glacier tongue as early as 1903, indicating the initial phase of the advance (Winkler, 1996b). A study of the morphology of the glacier tongues, especially at steep outlets, can prevent misleading interpretation of length-change data, or help to explain unusual data caused by methodological problems. Again, Bergsetbreen can be taken as an example. The disintegration and disappearance of the lower part of the ice fall during the past four years (Figure 3) gives a much more dramatic impression of the actual glacier behaviour than the length-change data. In addition, there are problems with what should be defined as 'glacier front' in connection with the length-change measurements: the frontal position of the lower, now stagnant glacier tongue at the foot of the ice fall, or the front of the active part of the ice fall. Because of this methodological problem, length measurements at Bergsetbreen stopped in 2006. There are other examples where the interpretation of the length-change series is complicated because of successive changes of the morphology of the glacier tongues (eg, Briksdalsbreen; Kjøllmoen, 2007). Some of the high annual retreat values given for the mid-twentieth century period are believed to result from disintegration of parts of the glacier tongue, or separation and down-melting of the lower tongue. If a detailed contemporary photographic record for that specific period existed (which is, unfortunately, not the case), useful information not only about the retreat mechanisms but also about today's development might be gained.

The ongoing regular visual monitoring of the glacier tongues started successively after 1989 by taking standardized photos of the glacier tongues from the same position at least annually

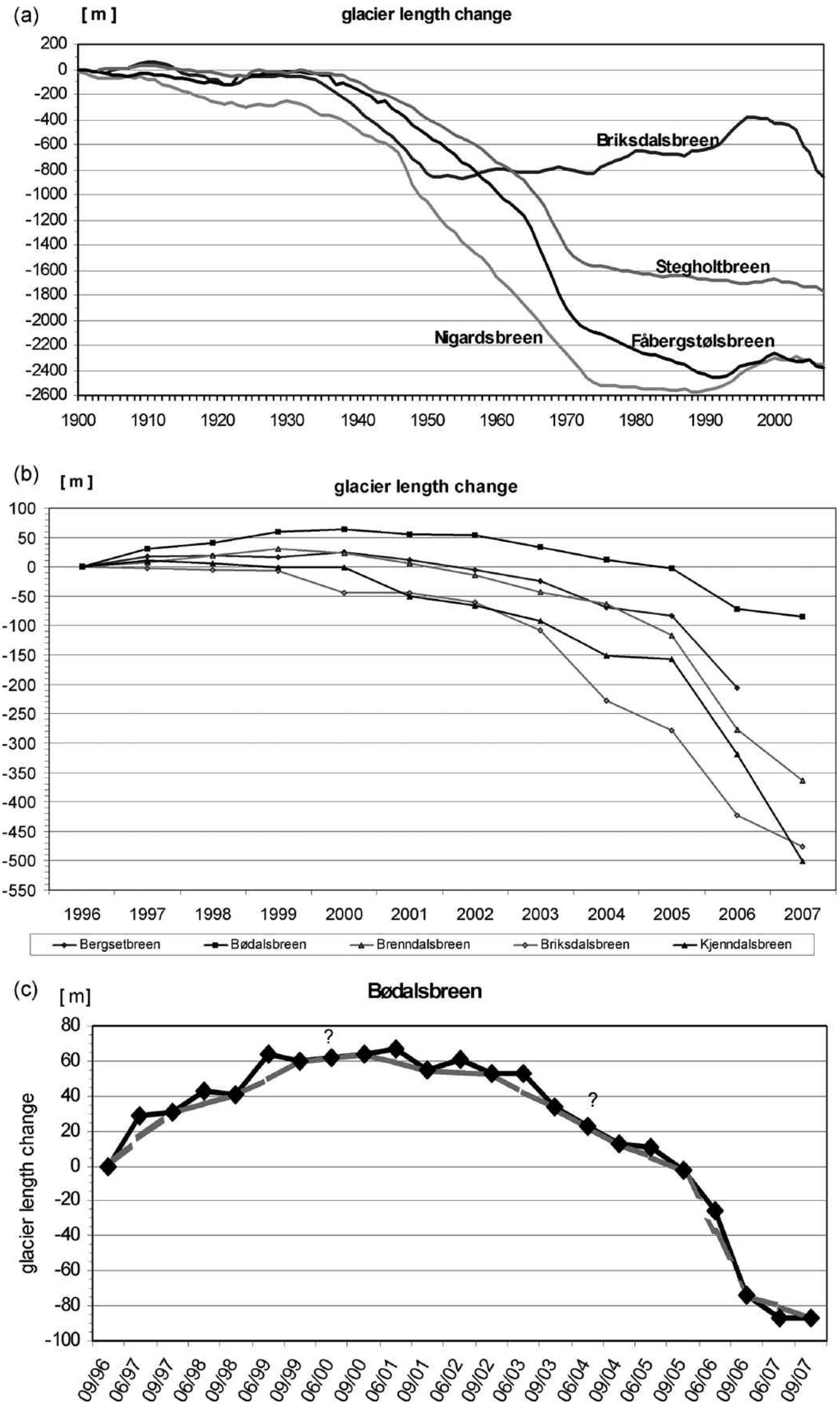

Figure 2 (a) Cumulative glacier length change of Briksdalsbreen, Fåbergstølsbreen, Nigardsbreen and Stegholtbreen, the only uninterrupted data series from Jostedalsbreen (data: NVE). Note that the revised length change data series for Briksdalsbreen (Kjøllmoen, 2007) has been applied for the whole study. (b) Recent cumulative glacier length change of the five monitored short outlets of Jostedalsbreen (data: NVE). The measurements at Bergsetbreen stopped in 2006 (cf. text and Figure 3). (c) Cumulative glacier length change of Bødalsbreen. The glacier was measured twice in most of the past years. The solid line gives this 'seasonal' length change, the broken line the annual change based on the main measurements in September. The strongest seasonal (winter) advance as measured from September to June at Bødalsbreen was +29 m (at Brenndalsbreen: +31 m; at Kjenndalsbreen: +20 m). The maximum summer retreat during the advance/stationary phases was −20 m at Bødalsbreen, −23 m at Brenndalsbreen and −10 m at Kjenndalsbreen (data: S.Winkler)

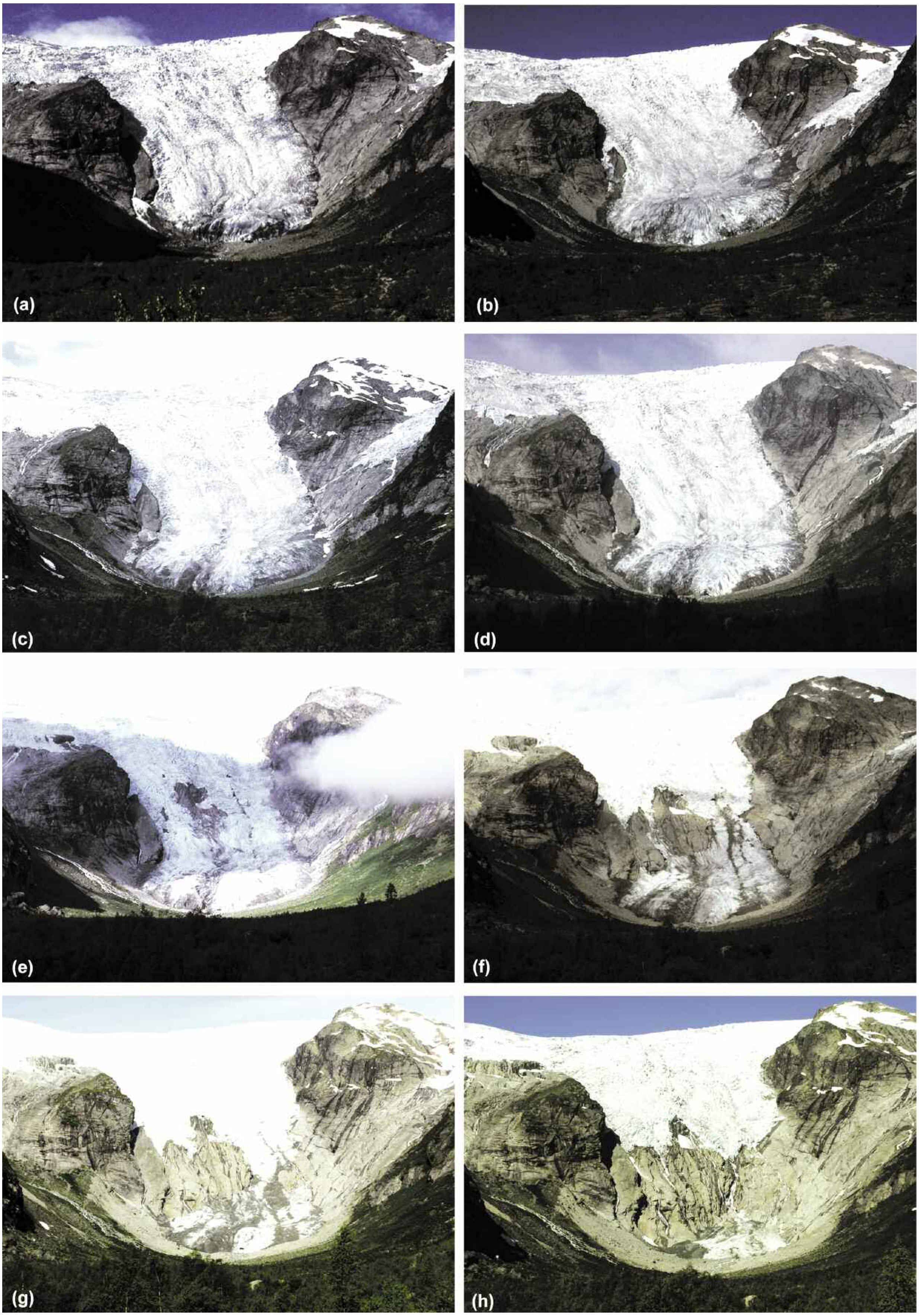

Figure 3 Photographic monitoring of Bergsetbreen, showing the impressive morphological change of its lower glacier tongue. Dates: (a) 30 August 1991; (b) 20 August 1995; (c) 22 July 1999; (d) 26 August 2002; (e) 22 August 2003; (f) 24 August 2004; (g) 27 June 2006; (h) 24 July 2008. The complete photo series of Bergsetbreen and 11 other outlet glaciers is available at: http://www.geographie.uni-wuerzburg.de/arbeitsbereiche/physische_geographie/weitere_forschungsarbeiten/norglamo

(see Figures 3–5). One original goal was to document glacier front position changes at those glaciers not measured annually in order to give at least an indication of the frontal changes. Especially in relation to glaciers starting to advance during the early 1990s, thickening of glacier tongues allowed some predictions about future ice-margin trends. Today, even at those glaciers where annual length change measurements later resumed, the visual information proved to be a valuable supplement. Single-year measurements that deviate from the multiyear trend, for example, can easily be related to changes of the geometry of the glacier margin or snow avalanches covering the glacier tongues during most of the ablation season (see below).

After a strong retreat that dominated the 1930s and 1940s, the short outlets of Jostedalsbreen went into a phase of slight frontal advance from the late 1950s/early 1960s, interrupted by a number of years with mainly stationary glacier fronts. The start of the advance at the short outlets is to some extent imprecise because there are missing observations, but the longer outlets continued to retreat well into the 1980s. In the late 1980s and during the 1990s, the advance accelerated at all outlets (cf. Winkler *et al.*, 1997; Konnestad Sorteberg, 1998; Andreassen *et al.*, 2005; Chinn *et al.*, 2005). The differential onset of the advance can be explained by differing individual terminus response times (Nesje, 1989; Winkler, 2002). Although, for Briksdalsbreen, annual measurements of length change are not available throughout the whole of the recent advance at the short outlets, observations of the glacier front prior to 1996 reveal annual advance distances exceeding 50 m at Bergsetbreen, Bødalsbreen, Brenndalsbreen and Kjenndalsbreen (Winkler, 1996a). Therefore, the high annual advance distances measured at Briksdalsbreen during the early 1990s were no exception, but occurred at the other short outlets at comparable magnitudes (cf. Konnestad Sorteberg, 1998).

The glacier-length records for five short outlets since 1996 are analysed in detail in this paper. Despite different absolute annual and cumulative values, the pattern of glacier-length change was comparable for all glaciers (Figure 2b, Table 2). Whereas the frontal glacier margin reached its outermost position at Briksdalsbreen as early as 1996, the termination of the recent advance at the other glacier occurred a few years later (Kjenndalsbreen: 1997; Brenndalsbreen: 1999; Bergsetbreen and Bødalsbreen: 2000). However, while the Briksdalsbreen ice margin was stationary from 1996 until 1999, the advance slowed down simultaneously at the other outlets. The early termination at Briksdalsbreen might have been influenced by special local conditions, namely the existence of a proglacial lake (Figure 4). After that advance phase ended, all glaciers underwent a short phase (up to three years) of stationary glacier margins or minor retreat. After this phase ended around 2002 (at Kjenndalsbreen in 2000), the recent considerable retreat began and is still continuing in 2008. The visual monitoring revealed that a large snow avalanche covering the entire glacier terminus until late summer 2005 caused the comparable small retreat at Kjenndalsbreen between 2004 and 2005 (−6.5 m). It caused a quasi-stationary glacier front and should not be interpreted as a turning point (as the retreat accelerated again in 2006).

During the recent glacier advance and the following retreat, visible changes of geometry and morphology occurred at most outlets of Jostedalsbreen. Those at the steep and short glacier tongues were most significant. The advance was accompanied by ‘typical’ morphological changes of the lower glacier tongues, leaving them steep, with a highly convex shape in profile and intersected by radial crevasses. During the most recent retreat at Bergsetbreen, bedrock was exposed within the ice fall for the first time in 2003 indicating substantial thinning in the ice fall (Figure 3). That bedrock ‘window’ was successively enlarging and the connection between the ice fall and the lower tongue was cut off between mid-June 2006 and mid-August 2006, although the upper ice fall seemed to have undergone some thickening during the same time. During the past few years, the lower tongue seems to be more or less stagnant and prone to melt down after now having lost the vital connection to the ice fall.

At Bøyabreen, the photo series (Figure 4) confirms a trend of ice mass increase and successive decrease after *c.* 2000 parallel to the other short outlets. The upper glacier and the secondary ice accumulation at the foot of the ice fall were connected in 1994, and the connection was most extensive in 1995. The connection was broken again in 2001. Kjenndalsbreen (Figure 5) probably reached its maximum position in spring 1996, even though autumn length change observations indicate the maximum position was reached in 1998. The ice fall seems to have been thickest around 1994. Melkevollbreen (Figure 5) has changed dramatically and simultaneously with the other steep outlets during the most recent years. Narrow glacier tongues located in narrow, gorge-like sections of glaciated valleys such as Kjenndalsbreen and Melkevollbreen are exposed to particularly strong frontal retreat as microclimatologic effects (eg, long-wave radiation from the valley walls) enhance the overall regional climate trend. Once thinning and narrowing, all steep and short glacier tongues below ice falls are subjected to possible detachment from the active glacier parts, leaving more-or-less stagnant ice complexes rapidly down- and back melting. This pattern was clearly visible during recent years and has to be taken into account of in relation to the pure numerical glacier length-change data. During the cold and moist summer of 2007, summer back melting was less pronounced at some of the outlets, as the retreat registered during the early summer visit in 2008. It is, however, too early to judge whether this development signals the end of the dramatic retreat.

Mass balance data

Mass balance measurements have been carried out at Nigardsbreen since the budget year 1961/1962 (Figure 6a; Andreassen *et al.*, 2005). As the accumulation area of Nigardsbreen is adjacent or close to the accumulation areas of the five short outlets, and all glaciers are part of the same ice plateau, the mass balance record of Nigardsbreen is considered highly relevant for the other outlets (Rasmussen and Andreassen, 2005). Mass balance data from Nigardsbreen has already been used successfully in a number of studies on the driving forces of the glacier variations, especially of the recent glacier advance during the 1990s (cf. Nesje *et al.*, 1995, 2000; Winkler *et al.*, 1997; Winkler and Haakensen, 1999; Winkler, 2001; Nesje, 2005; Andreassen *et al.*, 2005). In addition, the comparison of mass balance data of Nigardsbreen with other glaciers in southern Norway located on a W–E profile (Figure 6b) clearly demonstrates its maritime glaciological regime, and highlights the different trend at more continental glaciers in Jotunheimen which did not experience a comparable ice mass increase (Winkler, 2002; Rasmussen, 2004; Rasmussen and Andreassen, 2005; Andreassen *et al.*, 2005). However, an analysis of the relative annual trend of the net balance of the abovementioned glaciers on the W–E profile demonstrated surprising parallel deviations from the equilibrium state, ie, relative positive or negative net balance years often occurred at all glaciers with no obvious spatial differentiation. This finding suggests that the differences in glacier behaviour between the maritime western part of southern Norway and the more continental Jotunheimen represent different glacier responses to similar climate changes (cf. Winkler, 2002).

During the whole observation period between 1961 and 2007, there was a total increase in ice mass of 18 m w.e. (water equivalent) at Nigardsbreen. However, that mass was mainly added between 1961 and 1967 (+5 m w.e.), and especially in 1988–1995

Figure 4 Photographic monitoring of Briksdalsbreen (a–d) and Bøyabreen (e–h). Dates: (a) 30 August 1991; (b) 30 August 1995; (c) 25 June 2001; (d) 31 August 2006; (e) 03 September 1991; (f) 01September 1997; (g) 04 September 2002; (g) 20 June 2007

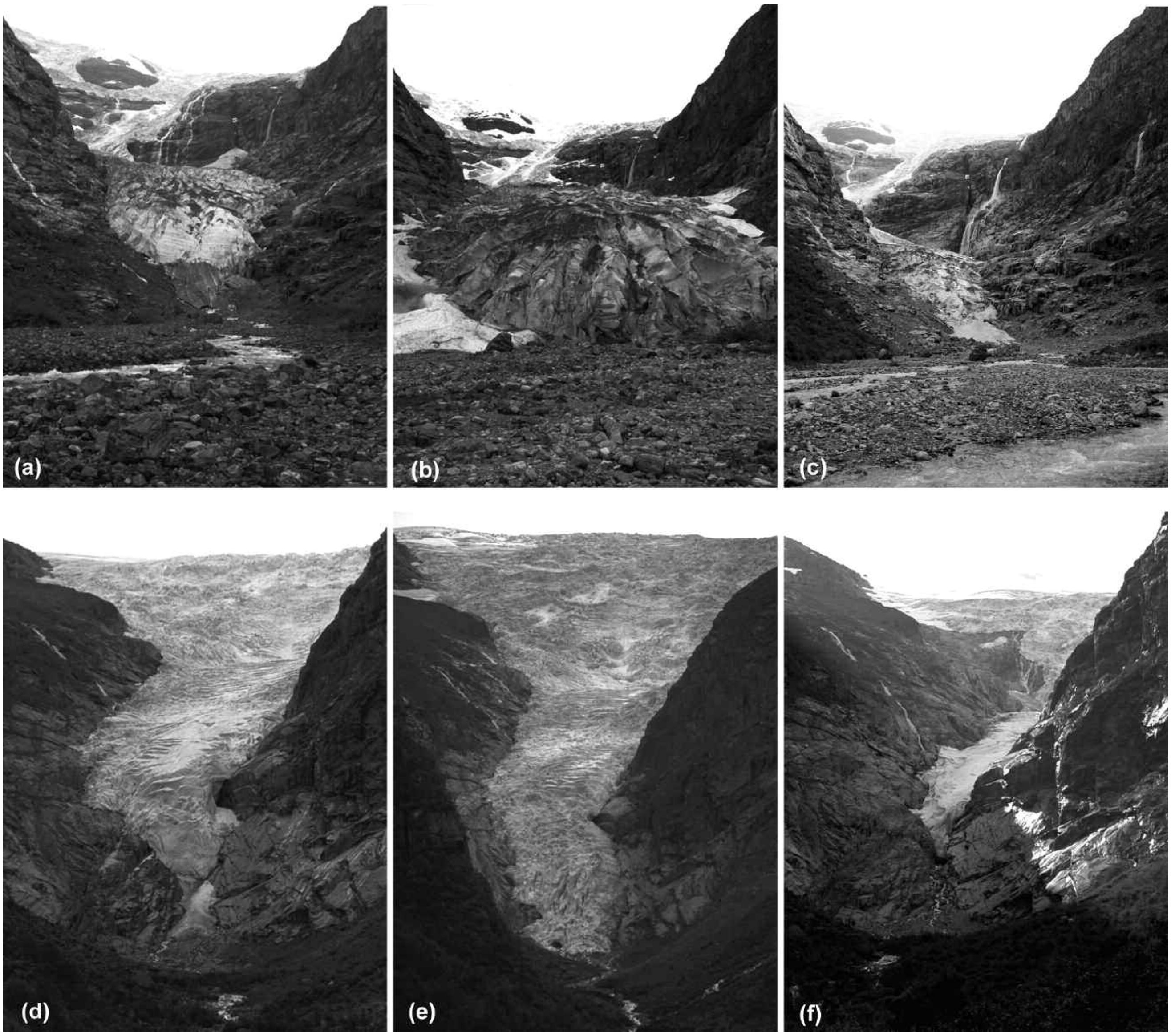

Figure 5 Photographic monitoring of Kjenndalsbreen (a–c) and Melkevollbreen (d–f). Dates: (a) 09 September 1991; (b) 19 June 1997; (c) 23 June 2006; (d) 07 September 1994; (e) 04 September 1996; (f) 31 August 2005

Table 2 Glacier length change data 1996–2006 for the five short glacier outlets studied in detail

Glacier	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Bergsetbreen	+ 25 m				− 30 m		− 201 m			
Bødalsbreen	+ 64 m				− 11 m		− 128 m			
Brenndalsbreen	+ 31 m			− 44 m			− 264 m			
Briksdalsbreen	− 7 m			− 415 m						
Kjenndalsbreen	+ 10 m	− 12 m			− 317 m					

The data are aggregated to multiyear periods representing advance, stationary front and retreat as mentioned in the text (data: NVE).

(+10 m w.e.). From 1967 until 1988, and between 1995 and 2007, the glacier was close to balance (+1.5 m w.e. and + 1.1 m w.e., respectively). Single years with considerable negative net balances (ie, > −0.5 m w.e.) occurred in 1966, 1969, 1970, 1977, 1980, 1988, 2002, 2003 and 2006. A mass loss of *c*. −2.5 m w.e. was recorded between 2000 and 2004. The highest cumulative value of the net balance series occurred in 2000 (+19.6 m w.e.). The highest positive net balance was registered in 1989 (+3.2 m w.e.), a remarkable turning point within the net balance series and the first year of the massive ice mass increase responsible for the 1990s advance.

The winter balance was approximately 0.7 m w.e./yr above average in 1989–1995. Previous budget years with recorded above-average winter balances did not occur consecutively to create a substantial increase in ice mass. In the same period 1989–1995 the summer balance was *c*. 0.4 m w.e./yr below average. Above-average winter balance combined with below-average summer balance substantially increased the glacier mass. The

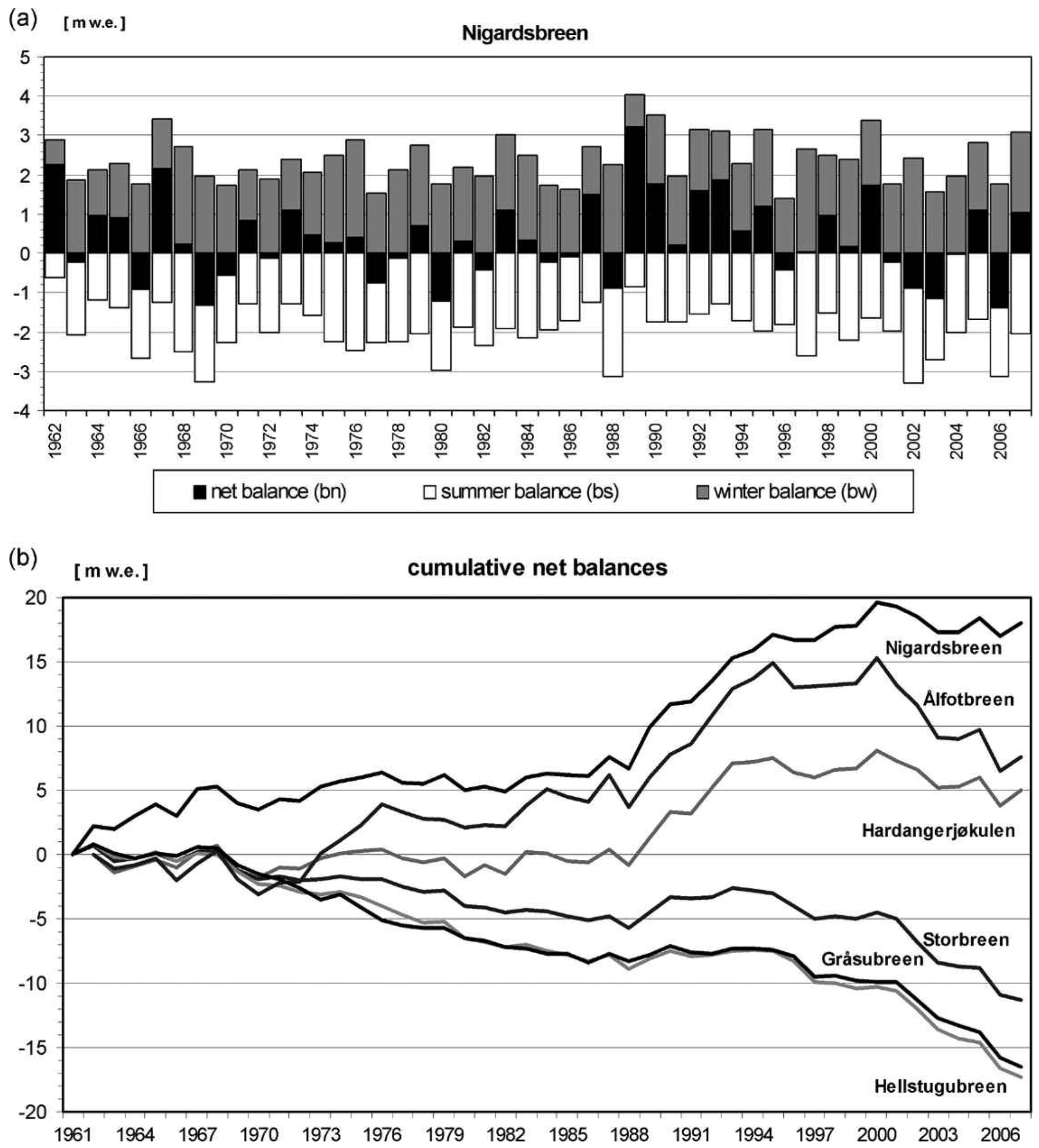

Figure 6 (a) Specific annual mass balance data for Nigardsbreen (data: NVE). (b) Cumulative net balance for Nigardsbreen during the observation period compared with five other glaciers in southern Norway located along a W–E profile (see Figure 1 for location; data: NVE)

budget year 1996 experienced the lowest winter balance of the whole record and caused a short break in the ice mass increase. During the following years until 2000 both balance terms were close to average, but between 2001 and 2006 the winter balance was more than 0.5 m w.e. below average in four out of six years. After 2000, four out of the seven years had summer balances with values around the average. In 2002, 2003 and 2006, years with marked negative net balances and substantial ice lost, summer balances well above average were recorded.

Causes of the glacier advance during the 1990s

In general, any change of the frontal position of a glacier tongue is a dynamic response to change of the glacier ice mass. The primary cause of any glacier advance or retreat is, therefore, a period of considerable positive or negative net balance. Mass balance data of Nigardsbreen are compared with the length change record at Briksdalsbreen in Figure 7a. The terminus response time, ie, the specific time lag between the occurrence of major mass balance disturbances and the first related change of the front position, is three to four years (Nesje, 1989; Winkler, 1996a). In general, a glacier terminus reacts primarily to a substantial disturbance of the net balance built up during several years rather than to single years of considerable deviations. A certain amount of perturbation of the (theoretical) equilibrium mass budget is necessary to cause the glacier terminus to respond in the form of an advance or retreat. Therefore, cumulative data series are more suitable for the actual analysis than annual data, apart from the abovementioned problem of variations in annual length-change data resulting from changes of the glacier tongue morphology.

Studies of the meteorological and glaciological reasons for the recent glacier advance in maritime southern Norway (eg, Nesje *et al.*, 1995, 2000; Winkler, 1996a, 2002; Winkler *et al.*, 1997; Nesje, 2005; Chinn *et al.*, 2005) point out the marked increase in

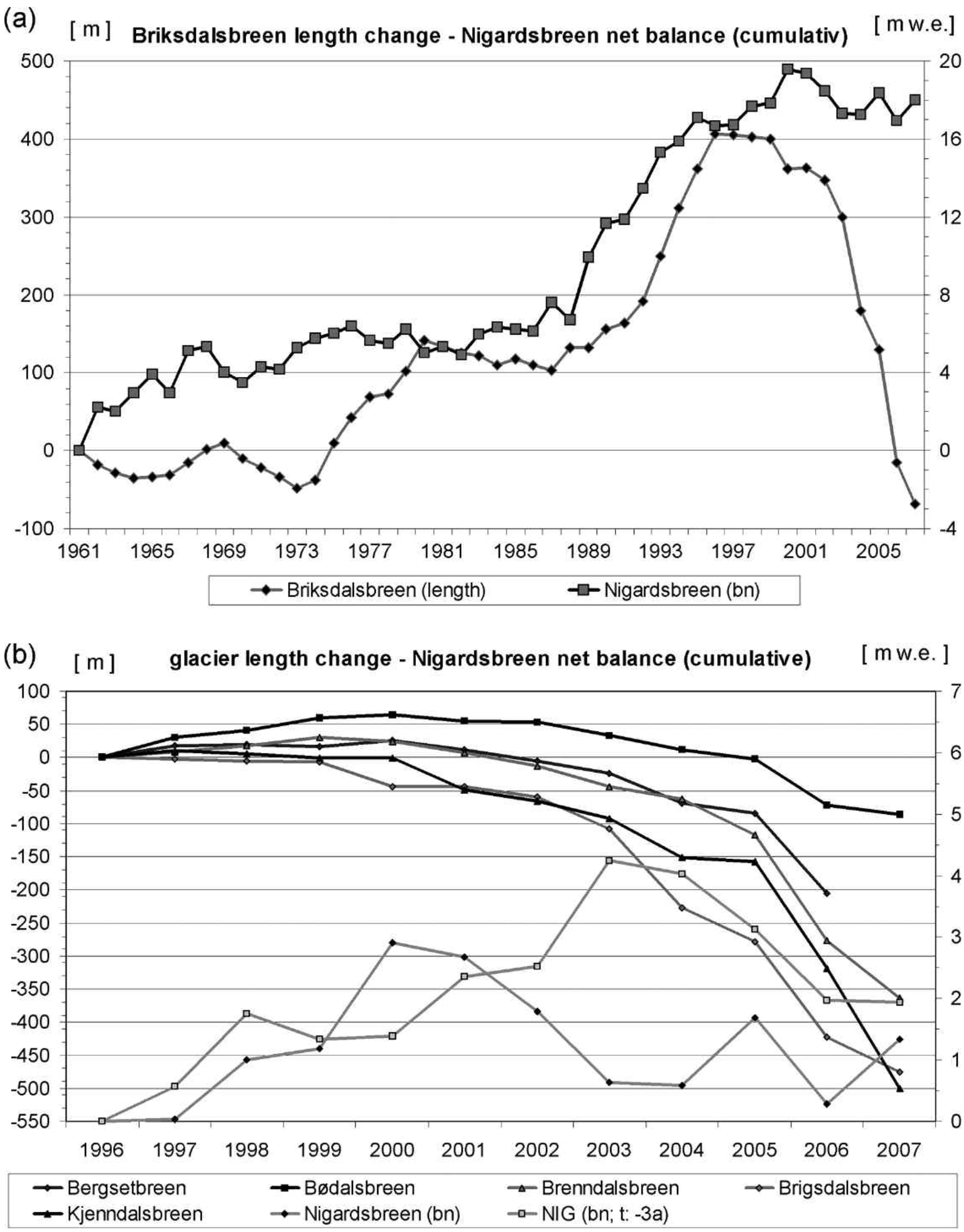

Figure 7 (a) Comparison of the cumulative glacier length change of Briksdalsbreen with the cumulative net balance of Nigardsbreen (data: NVE). (b) Comparison of the cumulative glacier length change of the short outlets of Jostedalsbreen with the cumulative net balance of Nigardsbreen (data: NVE). An additional theoretical net balance curve considering a terminus response time of three years (t:–3a) is given

ice mass registered at Nigardsbreen starting with the 1988/1989 budget year as responsible for the accelerated frontal advance at the short outlets. If the established terminus response time of three to four years is applied, this period of positive net balances and considerable mass surplus corresponds with annual position changes exceeding 50 m between 1992 and 1996 (accompanied by distinctive changes of glacier morphology). Analysis of meteorological data has enhanced our understanding of the underlying meteorological variations responsible for this mass balance development (Nesje *et al.*, 1995, 2008a; Winkler, 2001; Nesje, 2005; Nordli *et al.*, 2005). The meteorological record from Bergen is regarded as representative for the climate trends of maritime southern Norway (Liestøl, 1967; Nesje, 1989). Bergen has the longest continuous regional meteorological record. Data records of similar length from stations located closer to Jostedalsbreen have shown less significant correlation with mass balance or glacier length-change data than data from Bergen (Winkler, 2001; Nesje, 2005), and are consequently not recommended for such use (P.Ø. Nordli, personal communication, 2008). Non-representative orographic influence upon the meteorological data of those stations on a subregional scale is probably the reason for this. Only stations on a local scale, ie, directly in the vicinity of the individual glacier tongues, would deliver more accurate and representative meteorological data, but only for the lower glacier tongues. Unfortunately, those stations do not exist. The analysis therefore uses data from Bergen.

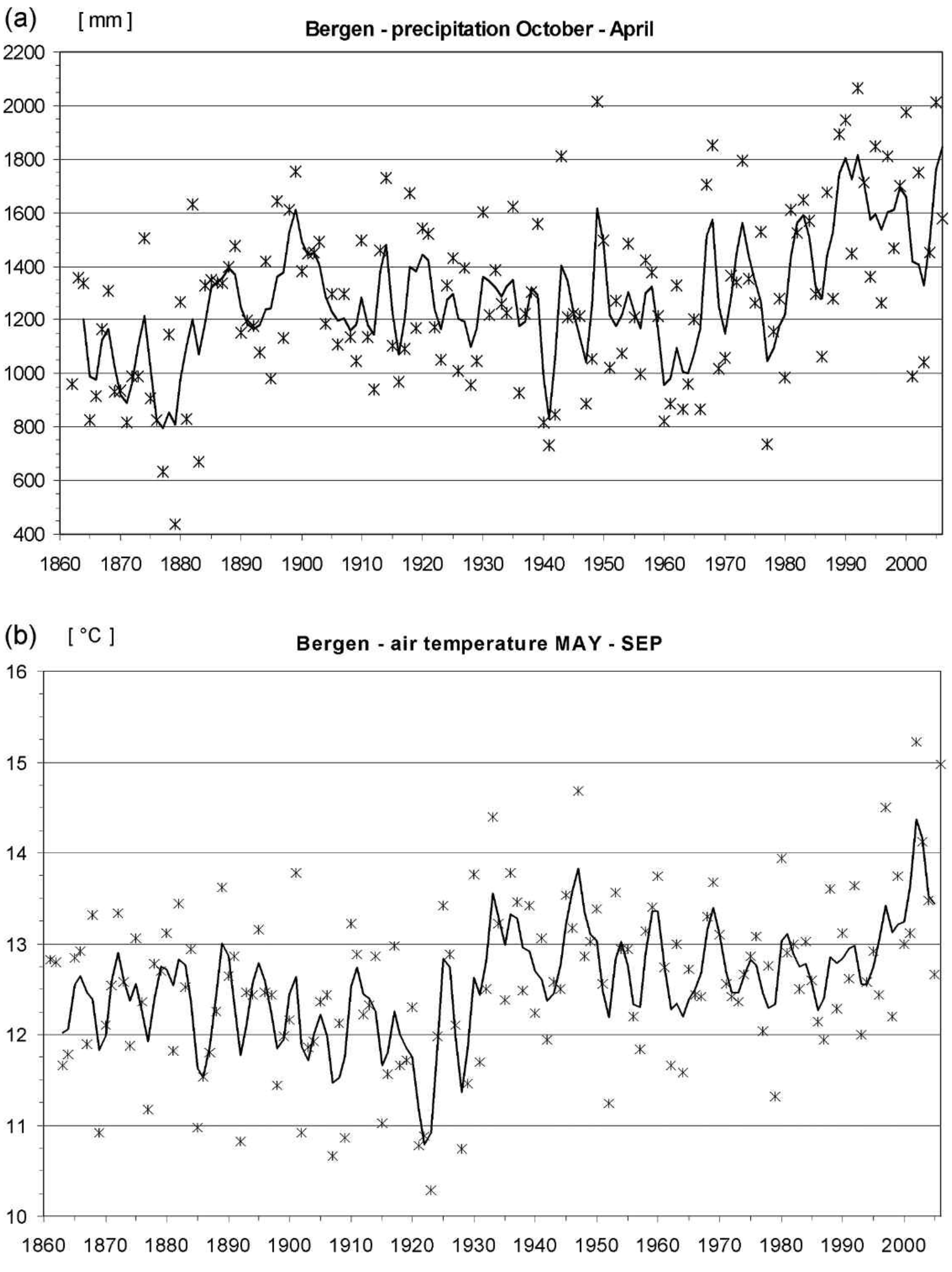

Figure 8 (a) Variations of winter precipitation (sum October–April) in Bergen (data: DNMI). The solid line represents a five-year Gaussian low-pass filter. (b) Variations of summer air temperature (mean May–September) in Bergen (data: DNMI). The solid line represents a five-year Gaussian low-pass filter

The winter balance of glaciers is mainly dependent on winter precipitation, while the summer balance is closely linked to summer temperature. The precipitation record (Figure 8a) shows increased winter precipitation during the last two decades of the twentieth century (Tables 3, 4a). In addition, during the 1990s, the period with highest winter accumulation, the precipitation maximum shifted from autumn into winter. Comparing the 10-year periods 1978–1988 and 1988–1998, a remarkable change in the seasonal distribution of precipitation is obvious, especially the marked increase for December through March (Table 3b). That change had a considerable effect on the glacier winter balance in western Norway (Winkler and Haakensen, 1999). The air temperature record shows high summer temperatures during the 1930s and 1940s and after 1997 and 1999 (Figure 8b). Until around 2000, there were no significant deviations of the summer air temperatures from the long-term means (Table 4b). Therefore, below-average summer air temperatures can be ruled out as a factor in the recent glacier advance. Winter temperatures, however, increased during recent decades and indicate a higher frequency of mild and moist southwesterly airflows (Winkler and Nesje, 2000). A strong zonal circulation

Table 3 (a) Average winter precipitation during three selected periods (cf. text) for Bergen (station Bergen-Florida DNMI 50540). The years stand for budget years (raw data: DNMI)

Period	Average winter precipitation (Σ October–April)
1989–1995	1753 mm
1996–2000	1643 mm
2001–2006	1471 mm
Normal (1961–1990)	1391 mm

(b) average precipitation during the 10-yr periods 1978–1988 and 1988–1998 (budget years) for selected summarized months for Bergen (raw data: DNMI)

Σ Monthly precipitation	Average 1978–1988	Average 1988–1998	Δ	Δ
May–April	2238 mm	2459 mm	+ 221 mm	+ 10%
October–April	1394 mm	1682 mm	+ 288 mm	+ 21%
December–March	693 mm	1094 mm	+ 401 mm	+ 58%
May–September	844 mm	777 mm	− 67 mm	− 9%

during the 1980s and 1990s is demonstrated by a high correlation between the NAO index (Hurrell, 1995; Dickson *et al.*, 2000) and winter balances of maritime glaciers (Pohjola and Rogers, 1997a, b; Nesje *et al.*, 2000; cf. Fealy and Sweeney, 2005; Bradwell *et al.*, 2006). The frequency and magnitude of storms increased during the 1990s (Schmith *et al.*, 1998), indicating high cyclonic activity. Summer precipitation decreased slightly during the 1990s (Table 3b), but it is not so important in the context of interpreting the glacier front behaviour. In summary, a relatively short period of increased winter snow accumulation was able to produce a substantial increase of ice mass, causing a considerable length change. With summer temperatures not significantly deviating from the long-term average, the period 1988 to 1995 provides a modern analogue to the scenario that is believed to have caused the glacier advance of the 'Little Ice Age' (Nesje and Dahl, 2003; Nesje *et al.*, 2008b).

Causes of the retreat after 2000

If the most recent retreat of the short outlets of Jostedalsbreen is analysed in the same way as the preceding advance or the glacier behaviour during the whole period since *c*. 1960, a surprising result emerges: the timing of the onset of the retreat and its magnitude during the past few years cannot fully be explained by the mass budget data (Figure 7a). The amount of ice mass loss since the budget year 2000/2001 is not large enough to explain the strong retreat observed and measured. The onset of the retreat and the proceeding period of stationary glacier fronts occurred 'too early' if compared with the cumulative net balance data series (especially if a terminus response time of three years is considered; Figure 7a, b). After 2001 and possibly already since 1997, the length-change data series and net balance data are divergent and are much less related than during the previous decades. As Nigardsbreen reached its highest overall mass gain in 2000 and the only (slight) break within this increase was in 1995/1996 (a cold and dry winter followed by an average summer season which resulted in a moderate negative budget year of −0.4 m w.e.), there is no indication of any turning point or strong signal for the termination of the recent advance at the time it actually happened. If the terminus response time is taken into account, the negative budget year of 1995/1996 should have caused a single year of stationary glacier margins around 1999 or 2000. In addition, the termination of the recent advance should have occurred three to four years after the cumulative net balance series reached its maximum (ie, in 2004/2005) which was not the case. The established relationship between mass balance and length change (see above) does not explain the actual glacier behaviour, ie, the retreat of the lower glacier tongues started prior to any substantial loss of ice mass. The magnitude of the ice mass lost since 2000 (*c*. −1.6 m w.e.) seems not to be as dramatic as the disintegration of some glacier tongues and annual retreat values of up to 160 m might indicate. One could characterize the most recent behaviour of the short outlets as unusually sensitive. Alternative hypotheses are necessary to explain why this development took place. Whether this phenomenon indicates major shifts within the glacier mass balance system and interactions/influence of the driving meteorological factors, or has to be explained by change/disturbance of the dynamic response of the glacier front to mass balance/climate variations, will be discussed later.

First, a corresponding meteorological data analysis seems to be an appropriate way of getting closer to an explanation (Tables 4, 5). Three multiyear periods have been outlined and used in further analysis representing the typical phases of frontal behaviour: (I) 1989–1995 (advance); (II) 1996–2000 (stationary front); and finally (III) 2001–2006 (retreat). Even though the average winter

Table 4 (a) Deviation of average monthly precipitation for Bergen (in mm) from the 1961 to 1990 normal, given for the specified periods. Corresponding net balance record for Nigardsbreen (last column) is given for comparison. Values are calculated for budget years (raw data: DNMI/NVE)

Period	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Σ bn
1989–1995	−105	−42	+106	+144	+77	+131	+51	0	+9	+10	+17	−60	+10.4 m w.e.
1996–2000	+47	−62	−3	+29	+172	+40	+10	−13	+8	−8	−17	−112	+2.5 m w.e.
2001–2006	−39	+36	+20	+67	+13	−44	+27	+12	+29	+10	−14	0	−2.6 m w.e.
Normal (1961–1990)	271 mm	259 mm	235 mm	190 mm	157 mm	170 mm	114 mm	106 mm	132 mm	148 mm	190 mm	283 mm	n/a

(b) Deviation of average monthly air temperature for Bergen (in °C) from the 1961 to 1990 normal, given for the specified periods. Values are calculated for budget years (raw data: DNMI/NVE)

Period	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Σ bn
1989–1995	−0.4	+0.5	+0.3	+2.4	+1.3	+0.9	+0.5	−0.1	−0.4	+0.4	0.0	+0.4	+10.4 m w.e.
1996–2000	0.0	+0.3	+0.4	+1.4	+1.2	+0.2	+1.0	−0.5	−0.3	+0.2	+1.5	+1.5	+2.5 m w.e.
2001–2006	+0.3	+0.9	+0.9	+1.5	+0.6	−0.9	+1.5	0.0	0.0	+1.9	+2.4	+1.9	−2.6 m w.e.
Normal (1961–1990)	8.6°C	4.6°C	2.4°C	1.3 °C	1.5°C	3.3°C	5.9°C	10.5°C	13.3°C	14.3°C	14.1°C	11.2°C	n/a

Table 5 (a) Regression analysis (r = correlation coefficient after Pearson) of different cumulative mass balance data series (bn, net balance; bw, winter balance; bs, summer balance) for Nigardsbreen with the cumulative length change data series of Briksdalsbreen. The three multiyear periods represent the frontal behaviour (cf. text). The series bn (t: –3a) and bn (t: –4a) take a terminus response time of three respectively four years into account. Because of that terminus response time, the longer time periods do not start in 1962, but in 1965 (1966) for those two series indicated by * (raw data: NVE)

Period	bn	bn (t: –3a)	bn (t: –4a)	bw	bs
1989–1996	$r = 0.88$	$r = 0.97$	$r = 0.98$	$r = 0.94$	$r = -0.97$
1997–2000	$r = -0.94$	$r = -0.24$	$r = -0.45$	$r = -0.88$	$r = 0.82$
2001–2006	$r = 0.64$	$r = 0.20$	$r = -0.66$	$r = -0.97$	$r = 0.95$
1962–1996	$r = 0.90$	$r = 0.93$*	$r = 0.94$*	$r = 0.91$	$r = -0.89$
1962–2006	$r = 0.84$	$r = 0.78$*	$r = 0.72$*	$r = 0.81$	$r = -0.79$

(b) Regression analysis of different air temperature series for Bergen with the cumulative length change data series of Briksdalsbreen. The temperature series are calculated as cumulative sum of monthly deviations from the 1961 to 1990 normal for different months (from right to left: July–September, July–October, June–October and May–September; raw data: DNMI/NVE)

Period	Σ ΔJ,A,S	Σ ΔJ,A,S,O	Σ ΔJ,J,A,S,O	Σ ΔM,J,J,A,S
1989–1996	$r = 0.81$	$r = 0.44$	$r = -0.10$	$r = -0.89$
1997–2000	$r = -0.76$	$r = -0.84$	$r = -0.75$	$r = -0.29$
2001–2006	$r = -0.95$	$r = -0.98$	$r = -0.97$	$r = -0.95$
1962–1996	$r = 0.76$	$r = 0.75$	$r = 0.38$	$r = -0.90$
1962–2006	$r = 0.45$	$r = 0.43$	$r = 0.33$	$r = -0.87$

precipitation decreased from phase I to phase III (Table 3a), it still remains above the long-term average (1961–1990 normal: 1391 mm; 1961–2005 mean: 1433 mm). During the last phase, the average winter balance was 0.3 m w.e./yr below the mean over the whole mass balance period and 0.2 m w.e./yr below the mean for the period between 1962 and 1988. In summary, analysis of the precipitation record for Bergen gives no significant deviations or trends that could explain the most recent glacier retreat.

Focusing the analysis upon summer air temperatures, the highest average air temperature for the combined months August/September since 1861 was recorded in 2002, followed by 2006 (Figure 9). This parameter was above the long-term average (1861–2005 mean: 12.8°C; 1962–2005 mean: 13.2°C; 1961–1990 normal: 12.7°C) in every year since 1999, apart from 2007 (a reason for excluding 2007 from phase III). The positive air temperature anomaly during the most recent years can easily be detected if single month deviations from the corresponding air temperature normal between phases I and III are compared (Table 4b). Whereas summer temperatures during the early 1990s remained close to average values, there was a significant rise in August and September temperatures during the second part of the 1990s, followed by a further increase after 2000 (that affected July and, to a minor extent, October). Apart from 2005 (eventually triggered by a above-average winter balance and large amounts of winter snow surviving well into the ablation season) and 2007, the summer balance was equal to or larger than the average after 2000 (0.5 m w.e./yr as mean), indicating high ablation rates. A high summer balance also occurred in 1997, the year with the highest single average for the combined months of June and July (16.4°C; 1962–2005 mean: 13.9°C; 1961–1990 normal: 13.8°C). However, for all three phases analysed, the month of June was (slightly) colder than normal. It can be concluded that the registered air temperature rise during the ablation season in most recent years mainly affected the second half of the ablation period from July until September with higher ablation values and a prolonged ablation season. Although the air temperature increase in October was not as high as during the proceeding month, the difference from the below-average temperatures in phase I can be interpreted in the same way, especially as the negative effect of any temperature rise in autumn has been demonstrated (theoretically) in previous studies (eg, Winkler and Haakensen, 1999).

In summary, analysis of the meteorological parameters for Bergen shows that the most obvious factor influencing the most recent glacier retreat at Jostedalsbreen is the rise of air temperatures during summer/late summer (July, August and September). However, it is not obvious why these meteorological conditions have not been correspondingly documented in the annual mass balance record, although there is little doubt that the lower glacier tongues were strongly affected by this excessive ablation. A number of hypotheses to explain the magnitude of the recent retreat and the failure of established relationships between glacier front behaviour and mass balance series after 2000 can be proposed as a basis for further discussion:

(a) the established relationships between mass balance and frontal behaviour are wrong in general;
(b) there is a systematic methodological error or uncertainty embedded in the net balance data series of Nigardsbreen (eg, overestimating the mass gain and/or underestimating the mass lost);
(c) the net balance series of Nigardsbreen is imprecise and not representative for the lowermost glacier tongues of the short outlet glaciers;
(d) the established relationship between mass balance and frontal behaviour (the dynamic response) is disturbed by the frequent occurrence of extreme high summer temperatures during most ablation seasons since *c.* 2000 (thus, terminus response times are negligible and lower glacier tongues almost exclusively affected by enhanced summer back melting);
(e) the glaciological regime has undergone a general shift towards more continental conditions, making the maritime glaciers of Jostedalsbreen more dependent on conditions during summer/ablation season and, as a result, on air temperatures.

Discussion

Mass balance measurements give direct information of ice mass changes caused by short-term climate variations (Meier, 1961, 1962; Meier and Post, 1962; Paterson, 1994; Dowdeswell *et al.*, 1997; Benn and Evans, 1998; Liestøl, 2000; Benn and Lehmkuhl, 2000; Nesje and Dahl, 2000). For investigations of the causes of

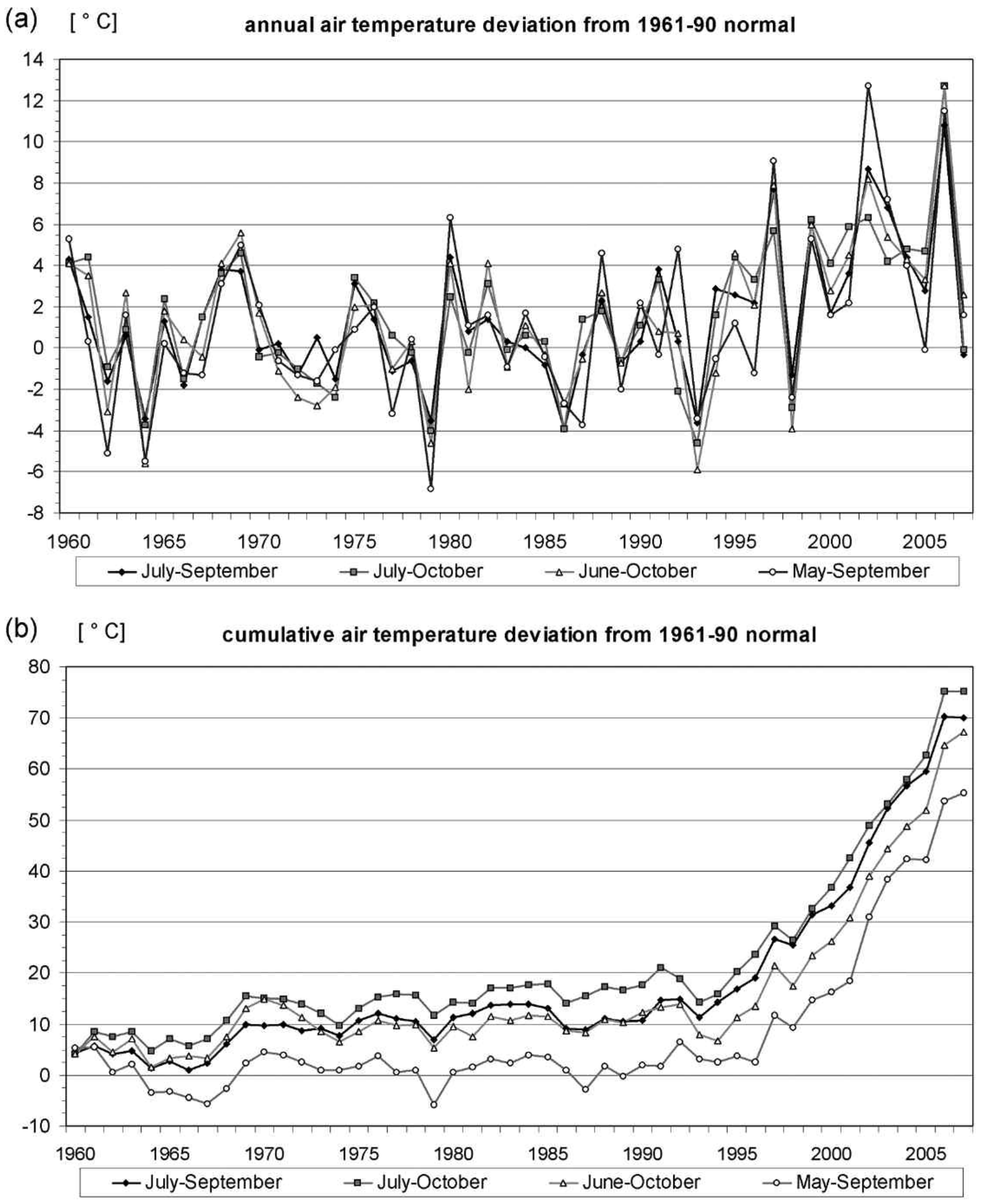

Figure 9 (a) Summarized annual deviation of the air temperature from the corresponding 1961–1990 normal, calculated for selected multimonth periods in Bergen (raw data: DNMI). (b) Cumulative presentation of the deviation data shown in (a)

glacier front position changes, mass balance data are preferable to data of meteorological parameters. However, any change of the ice mass as detected in net balance data will not immediately lead to a reaction of the glacier front, but to delayed response (Nye, 1965a, b; Moran and Blasing, 1972; Jóhannesson *et al.*, 1989, Hooke, 2005). In its use here this 'terminus response time' (or 'terminus reaction time') has to be distinguished from the 'response time' which is defined as the time it takes for a glacier to establish a new steady state after a mass balance perturbation (Raymond *et al.*, 1990; Paterson, 1994; Hooke, 2005). It is the latter that is used in the context of glacier modelling (Oerlemans, 1992, 2001, 2007; Braithwaite and Zhang, 1999; Weber and Oerlemans, 2003). Recently, Oerlemans (2007) calculated an ε-folding response time of five years for Briksdalsbreen on the basis of its length record and a simple model. Although he did not use the revised length record for Briksdalsbreen and applied a special filter in order to smooth the original data, his result is very similar to the empirically derived terminus response time of three to four years applied here, and can be regarded as an independent confirmation. In addition, Oerlemans (2007) stated that numerical flow line models (eg, Oerlemans, 1997, 2001; Leysinger Vieli and Gudmundsson, 2004) often tend to overestimate response times. All these findings and others (eg, Jóhannesson *et al.*, 1989) do not, however, explain the recent change of terminus response time from three or four years to almost none as has occurred recently. Salinger *et al.* (1983) applied different terminus reaction times for changes of air temperature (two years) and precipitation (five years) for the analysis of the frontal behaviour of Stocking Glacier

Table 6 Comparison of the specific winter (bw), summer (bs), and net balances (bn) of Nigardsbreen with two of the short outlets for three selected budget years. The values for Briksdalsbreen and Bødalsbreen are calculated using the individual altitudinal distribution of their area and the specific altitudinal balances recorded at Nigardsbreen in the corresponding budget years (raw data: NVE)

	Nigardsbreen	Briksdalsbreen	Bødalsbreen
1992			
bw	3.1 m w.e.	3.4 m w.e.	3.5 m w.e.
bs	−1.6 m w.e.	−1.4 m w.e.	−1.4 m w.e.
bn	1.6 m w.e	2.0 m w.e.	2.0 m w.e.
2005			
bw	2.8 m w.e.	3.0 m w.e.	3.0 m w.e.
bs	−1.7 m w.e.	−1.6 m w.e.	−1.6 m w.e.
bn	1.1 m w.e.	1.4 m w.e.	1.4 m w.e.
2006			
bw	1.7 m w.e.	1.8 m w.e.	1.8 m w.e.
bs	−3.2 m w.e.	−3.0 m w.e.	−3.0 m w.e.
bn	−1.4 m w.e.	−1.2 m w.e.	−1.2 m w.e.

(Southern Alps/ New Zealand). Because they operated with meteorological data only, their attempt can hardly be used at Jostedalsbreen. Even if the recent advance at Jostedalsbreen was mainly caused by precipitation and the most recent retreat by high summer air temperatures, the phenomenon pointed out by Salinger *et al.* should already be registered in the net balance data, as the mass budget directly responds to the actual climate conditions during the budget year.

Among the different methods to determine the specific annual mass balance of a glacier, the traditional or glaciological method of direct measurements on the glacier seems to be the most appropriate (Østrem and Haakensen, 1999; cf. Østrem and Brugman, 1991). It is applied at Nigardsbreen and all mass balance data used in this study are derived by this method. Tests using the specific altitudinal distribution of two of the short outlets, Bødalsbreen and Briksdalsbreen, have revealed no significant differences to the net balance series of Nigardsbreen (Table 6). However, Kuhn (1989) pointed out that annual mass balance data *per se* have a transient effect because they are an average over the whole glacier surface. He therefore concluded that the mass-balance gradient (the gradient of the curve representing altitudinal variation of the mass balance of the glacier surface; Kuhn, 1984; Oerlemans and Hoogendoorn, 1989) and the equilibrium line altitude (ELA) might be a better measure of the status of a glacier than the averaged mass balance. The ELA-record of Nigardsbreen experienced the highest calculated ELA for 2003 and a high value for 2006, but reveals no specific trend for the most recent years. That is not surprising, as the calculation of the ELA itself is based on the same mass budget data represented by the net balance data series found to be incapable of fully explaining the recent retreat. However, it has already been confirmed in several previous studies that mass balance data yield significant explanations for the glacier terminus response at Jostedalsbreen during the whole period with available data up to *c*. 2000. In addition, comparable findings of the significance of mass balance data in the interpretation of frontal behaviour have been reported from mountain glaciers elsewhere (Nesje and Dahl, 2000; Hoelzle *et al.*, 2003; Chinn *et al.*, 2005; IPCC, 2007).

Hypotheses (a) and (b), therefore, seem very unlikely. But it is possible that the mass balance data traditionally calculated and averaged over the whole altitudinal range of the glacier surface might not fully reflect the ice mass development at the lower glacier tongue affected by enhanced summer back melting (hypothesis c). At Nigardsbreen, there are no stakes on the lowermost 250 m of the glacier: the related mass balance data for this altitude is therefore calculated from empirical relations and formula. As a consequence, the mass balance gradient owns some restriction in its interpretation. Except for 1998, the gradient over the most recent years was merely around the long-term average. The specific winter balance values for the lowest part of Nigardsbreen show negative values after 2000. These data might be influenced by methodological factors mentioned above, but are more likely to have been caused by a prolonged ablation season extending well into late autumn with its definite end postdating the annual ablation season measurements. The net balance for the lower part of Nigardsbreen delivers a parallel trend to the glacier terminus at the short outlet glaciers. Neglecting any terminus response time, two years of very negative net balances for the lower parts in 1997 and 1998 correspond to the stationary glacier fronts. Another period of extremely negative net balance for the lowest altitudinal intervals of Nigardsbreen started with the budget year 2001, ie, parallel to the onset of the most recent retreat. For the period from 1996 until 2006, the specific net balance of the lowest part of Nigardsbreen seems to be a fairly useful indicator of the frontal behaviour. However, during the period of strong advance, no such parallelism was apparent, indicating that the net balance of the lowest parts of Nigardsbreen, if at all, could act as indicator only in the most recent situation of above-average high ablation during (late) summer.

The lack of any terminus response time could point towards a decoupling of the lower glacier tongues form the system of dynamic response to changes in ice mass. Moran and Blasing (1972) point out that a glacier front would react immediately to a temperature rise if the lower glacier tongue were stagnant. The ice velocity measurements carried out at Briksdalsbreen (Kjøllmoen, 2001) showed that although ice velocities decrease after 1996/1997 towards the end of a period with a stationary glacier front, there was no stagnant ice detected at the lower glacier tongue. There was no stagnant ice observed during the past few years at the other glaciers, either. The lowermost tongue of Bergsetbreen became stagnant as a result of and not a reason for the retreat.

Regarding hypotheses (d) and (e), there are some indications that a temporary or permanent regime change in the relationship between single meteorological parameters, mass balance and front position change might have happened during the most recent years. Regression analysis of different meteorological and glaciological data series reveals some dramatic differences between the results for the periods 1962–1996 and 1997–2006 (Tables 4, 5). Most significant is the result for the net balance versus length change, giving a high degree of explanation prior to 1997 (and especially for the advance period 1988–1996), whilst there is no useful correlation detectable for the later period, especially when the terminus response time is taken into account. By contrast, a statistically significant correlation that emerged during the most recent years is the strong negative correlation of the deviation of summer air temperatures and the length changes. In fact, there is a clear statistical signal that the positive anomaly of summer air temperature experienced since 1997 (and accelerating after 2001; cf. Table 4b) is the main reason for the strong retreat measured during the last years. As this and other relating regressions gave different results for the proceeding decades (Winkler, 2001), the two hypotheses mentioned above are strengthened, although it is too early (and the period too short) to judge whether the regime change is permanent or just temporary (ie, a disturbance of the existing patterns).

It is not easy to detect a clear ‘turning point’ (ie, budget year) within the mass balance record that could be related to the onset of the most recent retreat. Since the cumulative effect of several years is the important factor, one turning point alone might not be detectable anyway. However, one such potential turning point is

1996 with the first negative net balance after seven years of substantial ice mass increase. But as the negative net balance of 1995/1996 has to be classified as comparatively 'moderate', no substantial effect on the glacier tongues would be expected. Although the following budget year (1996/1997) was balanced, it could have played a key role. The summer balance was very high and June and July experienced record high air temperatures causing above-average summer back melting, ie, patterns that are believed to have taken place for most of the twenty-first century. Especially at the steep and low-lying glacier tongues of Briksdalsbreen and Kjenndalsbreen, that year clearly was a turning point and visually impacted them. As the next budget years until 2000 all experienced balanced or positive net balances and the ice mass increase continued, that year was not the immediate onset of the recent retreat, but of a stationary phase or the final slowdown. At Briksdalsbreen the ice velocity slowed down after the summer of 1997 (Kjøllmoen, 2001).

One interesting question is why there seems to be no terminus response time during recent years (Figure 7), which appears to contradict the principle of mass flux and dynamic response of the glacier front to the mass balance (Paterson, 1994; Liestøl, 2000; Nesje and Dahl, 2000). Previously, one or two consecutive negative budget years within the mass balance record of Nigardsbreen (eg, 1969–1970, 1977–1978) had no detectable consequence for the front position and terminus response time. In general, the permanent transfer of ice from the accumulation to the ablation area compensates altitudinal differences in accumulation and ablation. The glacier velocity responds to an increase (or decrease) in ice thickness caused by variations in mass balance (Benn and Evans, 1998). Prior to and during frontal advances, glacier velocities normally increase in order to transfer the mass surplus to the lower part of the glacier. This ice velocity increase might peak as early as one or two years after mass balance perturbations (Kuhn *et al.*, 1996). This is the direct link to the phenomenon of terminus response time. The mass surplus of positive mass balance years normally will be concentrated in the upper accumulation area of a glacier. This ice mass has to be transferred to the lower part of the glacier before the glacier tongue can react in the form of an advance. In a period of negative budget, a decrease in mass transfer and, as a result, in ice velocity will cause the glacier front to retreat, but again with a delay because the shape of the glacier tongue must change through melting from a thick, steep terminus to a thin, wedge-shape morphology. At Briksdalsbreen, this transition lasted from 1996 until 2000. Seasonal glacier front variations demonstrate this relationship between mass surplus transferred from the accumulation area (influenced by the ice velocity) and frontal back and/or down melting at the glacier tongue by ablation. Why does that behaviour seem to be perturbed during the most recent retreat?

Owing to their specific climatic environment, maritime mountain glaciers are characterized by a high mass turnover and by high mass-balance gradients. Large altitudinal differences in winter, summer and net balance between lower and upper parts are typical. Appreciable seasonal glacier front variations ('winter' advance and summer back melting) are a consequence of this maritime glaciological regime (Figure 2c). The frontal retreat of the low-lying glacier tongue might primarily reflect any change in the 'normal' mass flux to the lower part of the glacier (ie, dynamic response to the net balance). But in most recent years characterized by high summer temperatures and a prolonged ablation season well into autumn, glacier tongues located at low altitudes will be extremely affected under such special climatic conditions. It seems that the glacier terminus is responding more in accordance with the actual weather condition at lower altitudes (in the form of an excessive summer back melting) than with the ordinary overall mass budget situation, as observed until *c*. 2000. The mass transfer is not able to respond quickly enough in order to compensate the ice lost at the lower glacier tongue. This extreme summer back melting and ablation at the lower tongues therefore cause a form of excessive mass loss not registered in the annual mass balance, and has not taken place during the previous four decades of continuous mass budget studies. In addition, the short outlets previously showing all the signs of a typical maritime glacier strongly influenced by precipitation patterns (cf. Nesje, 1989, 2005; Nesje *et al.*, 1995, 2000; Winkler, 1996a, 2002; Winkler *et al.*, 1997) seem to have become much more sensitive to summer air temperatures and the length of the ablation period (cf. Table 5b).

Varying local conditions support the idea of a disturbance of 'normal' dynamic response mechanisms. Kjenndalsbreen experienced a strong retreat during the last years, whereas Bødalsbreen showed the smallest retreat distance (Figure 2b). Although both glaciers are located near each other in Lodalen and have the same aspect, the Bødalsbreen terminus is ~450 m higher. That difference would be an important factor impacting on air temperatures and melting rates in the ablation season. In addition, the difference in glacier shape has to be taken into account. Bødalsbreen has a broad tongue flowing relatively gently down from the plateau. Negative microclimatologic effects are unlikely to occur here. Kjenndalsbreen has a very narrow lower glacier tongue where an 'oasis effect' (Oerlemans, 1989) with more sensible heat flow from the surroundings might enhance the ablation rate. This alone, however, does not provide a satisfying solution. At Briksdalsbreen, the special situation of calving in the once ice-covered and now again ice-free lake Briksdalsvatnet could lead to enhanced local melting, but the frontal behaviour of the non-aquatic short outlet glaciers is simultaneous. It seems likely that in years with extraordinary high ablation values, especially low-lying, steep and narrow glacier tongues might be extremely sensitive to excessive ablation.

Existing models and simulations for Jostedalsbreen and other glaciers in southern Norway (eg, Oerlemans, 1986, 1997, 2001, 2007; Laumann and Reeh, 1993; Jóhannesson *et al.*, 1995) provide no satisfactory explanation for the most recent retreat and the apparent lack of any terminus response time. A number of those studies operate with meteorological and mass balance data and deliver no detailed prediction of future changes of the glacier length (eg, Laumann and Reeh, 1993; Jóhannesson *et al.*, 1995). Those models with an incorporated flow-line model (eg, Oerlemans, 1986, 1997) only focus on Nigardsbreen and are long-term simulations with a response time of several decades to achieve an equilibrium with present climatic conditions. With that long response time and the lack of realistic flow-line models for the short and steep outlets because of the lack of data about glacier bed topography, velocity and ice thickness, these models cannot be applied here. Furthermore, most models use long-term means of meteorological parameters, and filter the empirical mass budget or length-change data available. This methodological aspect is another reason why those studies have not been tested further in the context of this study. Furthermore, the occurrence of excessive ice lost at the lowermost glacier tongues not registered and included in the annual mass budget is, in contrast to the impact of diffusion, not considered in existing models (cf. Marshall, 2006).

During the overall retreat of the short outlet glaciers since the 'Little Ice Age' maximum, the magnitude of the recent retreat seems only comparable with the strong retreat in the 1930s and 1940s. Unfortunately, there are no mass balance data available to test the hypothesis that this earlier retreat was also influenced by excessive ablation at the lowermost glacier tongues disturbing the dynamic response of the glacier. A vague hint might, however, be the fact that two readvances measured at the short outlets during the first and the third decades of the twentieth century did not occur at the long outlets with long terminus response times (Winkler, 1996b). The mass surplus that caused these readvances should have been effective at the long outlets during the 1930s and 1940s. As summer temperatures were high during this period, excessive ablation could have overcompensated the advance expected from the dynamic response to the mass budget. Because earlier major readvances and stillstands interrupting the retreat from the 'Little Ice Age' maximum position after AD 1750 are believed to have occurred at all outlets in more-or-less comparable numbers (Bickerton and Matthews, 1993), the non-participation of the long outlets in those two early twentieth-century readvances has at least to be pointed out.

The ultimate test for the hypothesis of a temporary disruption of the 'normal' mechanisms of terminus response to mass balance perturbations versus the hypothesis of a permanent change of the glaciological regime is not yet available. During the summer of 2008, there were just vague indications pointing towards a slowing of the retreat. It is possible, therefore, that the maritime glaciers of Jostedalsbreen are actually in a transient phase towards a more 'continental' glaciological regime, ie, a stronger dependency on the summer air temperatures and conditions during the ablation season. As a consequence, previous calculated terminus response times probably have to be revised with respect to the current meteorological and glaciological data. A number of such concerns and uncertainties need to be addressed in any interpretation of the most recent retreat and related glaciological data. This precaution relating to the most recent retreat at Jostedalsbreen is essential because the glacier length-change data from Jostedalsbreen fits well with to the glacier shrinkage reported from most other high mountain regions worldwide and could easily be misinterpreted.

Although some details about the mechanism of the most recent retreat remain unknown, it is very likely that excessive ablation during the (later part of the) ablation season resulting from unusual high summer air temperatures was the major cause of an enhanced summer back melting of the lower glacier tongues. That excessive ablation on the lowermost glacier tongues was not fully registered by the conventional mass balance measurements, leaving a considerable discrepancy between the length change and the mass balance data series, and changing the terminus response time to zero (= immediate response). Unfortunately, missing meteorological measurements on or in the immediate vicinity of the lowermost tongues make it impossible to quantify this 'extra' mass loss. As this meteorological data are missing, and local information on the glacier bed and ice velocity are also not available for the lower tongues, it is also not possible to model this 'extra' mass loss. However, this finding has to be pointed out for a correct interpretation of the most recent length change in relation to the mass budget and the climate variations responsible for it. For models incorporating the length-change data or for simulation of the length changes, it is important to consider the possible errors caused by such an 'extra' mass loss, which ensures that the response of a glacier front is not purely dynamically determined by the conventional mass balance data. The use of long-term average meteorological and glaciological data including the period of the most recent retreat and also the strong retreat during the 1930s and 1940s need therefore to be reconsidered in the light of possible substantial changes of factors such as terminus response time.

Even if some questions related to the mechanism of the most recent retreat remain open, the short outlet glaciers of Jostedalsbreen have delivered an excellent example of the highly sensitive response of maritime glaciers. They have demonstrated that both substantial advance and retreat over distances of several hundreds of metres can occur during relative short periods of just seven to eight years. Periods of up to ten years can be crucial for the glacier and its response to the climate. That sensitivity clearly is an argument against the (unquestioning) use of long-term mean values of glaciological parameters in glacier modelling. The potential source of error and uncertainty identified here could explain why no model is able to simulate accurately the most recent glacier fluctuations. The differences in terminus response time and the changing correlation between glaciological and meteorological parameters over relatively short periods (Table 7) have additionally to be taken into account as such 'mode changes' seem fairly characteristic for maritime glaciers.

Table 7 Brief and simplified comparison of some characteristics typical for the short outlets of Jostedalsbreen during the two different recent situations (advance/retreat)

Advance period (1989–1995)	Retreat period (2001–2006)
Net balance highly positive (+ 10.4 m w.e.)	Net balance negative (– 2.6 m w.e.)
Winter balance above average (0.7 m w.e. yr)	Winter balance slightly below average (0.3 m w.e. yr)
Summer balance slightly below average (0.4 m w.e. yr)	Summer balance above average (0.5 m w.e. yr)
Winter balance primarily forcing net balance	Summer balance primarily forcing net balance
Increased winter precipitation (snow accumulation)	Average winter precipitation (snow accumulation)
Average summer air temperature (ablation)	Increased summer air temperature (ablation)
Winter precipitation major forcing factor	Summer air temperatures major forcing factor
Terminus response time 3–4 years	Terminus response time zero (immediate response)
Frontal behaviour purely dynamic response to ice mass change (= fully detectable in mass budget data series)	Frontal behaviour *not* purely dynamic response to ice mass change due to excess ablation at tongue (= *not* fully detectable in mass budget data series)
Established empirical mechanisms and models can be applied	Established empirical mechanisms and models cannot be applied
Typical characteristics of maritime glaciers	Partially characteristics of continental glaciers

Conclusions

On the basis of the analysis of glacier length-change records, glacier mass balance data and meteorological data, the following conclusions about the recent front variations of the short and steep outlets of Jostedalsbreen can be drawn.

(1) The latest glacier advance came to an end between 1997 and 2000 at the steep outlets of Jostedalsbreen. During the advance of the 1990s, the lower glacier tongues underwent impressive and visible changes of their morphology. It has previously been shown that this advance was in response to a substantial increase in ice mass especially during the years 1989–1995. Major cause of this ice mass increase was an increase in winter precipitation/winter snow accumulation. A terminus response time of three to four years between mass balance perturbations and the related glacier length change was observed during this advance. That terminus response times could empirically be applied for the whole twentieth century.

(2) After 2000, the short outlet glaciers started to retreat. At most glaciers, this retreat extended to comparatively long distances and was, in a few cases, accompanied by a partial disintegration of the lower glacier tongue. The highly negative net balances were recorded in 2002, 2003 and 2006. According to the established terminus response times, the frontal response to that

mass lost should not have been detectable prior to *c*. 2004/2005. The ice lost recorded by traditional mass budget studies since 2000 has been of insufficient magnitude to account for the scale of the most recent retreat. This retreat cannot be explained by the use of the empirical relation between mass balance and length change applied prior to 2000.

(3) The air temperature record from Bergen shows above-normal air temperatures in August and September during the period 1996–2000, and strong above-normal air temperatures in July, August and September 2001–2006. The meteorological trend can clearly be related to the post-2000 glacier retreat. These above-average summer temperatures caused high ablation at the lower glacier tongues and enhanced annual summer back melting at the glacier tongue, and contributed to the high retreat distances recorded.

(4) By contrast to the situation prior to 1997, there is no obvious signal in the overall (averaged) net balance record for the timing and magnitude of the most recent retreat. Only the mass balance data for the lowest parts of Nigardsbreen give an indication, but their evidence is fairly limited because of methodological reasons. Terminus response times seemed to have changed in favour of an immediate response. Excessive ablation and extreme summer back melting cause an 'extra' ice loss not registered in the traditional mass balance data and disturbing the dynamic response of the glacier front to the mass flux. Whether this disturbance is of temporal character and restricted to a rather short period of extreme weather conditions between 2000 and 2006, or the glaciers have undergone a major change in glaciological regime towards a more 'continental' one cannot yet be judged.

(5) The latest advance and retreat of the short outlet glaciers of Jostedalsbreen are good examples of the sensitive response of maritime glaciers to climate fluctuations. The retreat after 2000 is an example of how special weather conditions might disturb or even disrupt established empirical relations between glacier change and mass balance perturbations. Under changing climatic conditions, extra caution is necessary within complex simulations and models. Excess ablation not registered in the traditional mass balance data (as has demonstrably occurred at the short outlets of Jostedalsbreen since 2000) has yet to be considered in such models.

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