ELSEVIER

Norwegian mountain glaciers in the past, present and future

Atle Nesje [a,c,*], Jostein Bakke [b,c], Svein Olaf Dahl [b,c],
Øyvind Lie [c], John A. Matthews [d]

[a] *Department of Earth Science, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*
[b] *Department of Geography, University of Bergen, Fosswinckelsgate 6, N-5007 Bergen, Norway*
[c] *Bjerknes Centre for Climate Research, Allégaten 55, N-5007 Bergen, Norway*
[d] *Department of Geography University of Wales at Swansea, Singleton Park, Swansea, SA2 8PP, United Kingdom*

Abstract

Documentation of glacier changes is a key element for reconstruction of past climate variability and early detection of global climate change. In this paper, records of Holocene glacier variations in different regions in Norway have been synthesised. During the period from approximately 8000 to 4000 cal. yr BP, most glaciers in Norway were completely melted away at least once due to high summer temperatures and/or reduced winter precipitation. Lichenometrically and historically dated moraines at Jostedalsbreen, in Jotunheimen, at Hardangerjøkulen, and at Folgefonna were used to extend records of glacier length variations back to their maximum position during the 'Little Ice Age'. The timing of the maximum 'Little Ice Age' glacial advance in different parts of southern Norway varied considerably, ranging from the early 18th century to the late 19th century. Cumulative glacier length variations of glaciers in southern Norway show an overall retreat from ∼AD 1750 to the 1930s–40s. Thereafter, most Norwegian glaciers retreated significantly. Short maritime outlet glaciers with a short response time (<10–15 yr) started to advance in the mid-1950s, whereas long outlet glaciers with longer frontal time lag (>15–20 yr) continued their retreat to the 1980s. In the 1990s, however, several of the maritime glaciers started to advance as a response to higher winter accumulation during the first part of the 1990s. Since 2000 most of the observed glaciers have retreated remarkably fast (annual frontal retreat >100 m) mainly due to high summer temperatures. The last glacier inventory in Norway published in 1988 shows that there were 1627 glaciers covering a total area of 2609 km^2 with an estimated volume of 164 km^3. Modern climate–glacier relationships from mass balance data in Scandinavia have been used to present possible effects on the Norwegian glaciers of climate scenarios between 1961–1990 and 2070–2100 presented by the 'RegClim' project. This long-term weather 'forecast' for western Norway indicates a rise in the summer temperature of 2.3 °C and an increase in the winter precipitation of 16% by the end of the 21st century. This climate scenario may, if it occurs, cause the equilibrium-line altitude (ELA) to rise 260 ± 50 m. As a result, about 98% of the Norwegian glaciers are likely to disappear and the glacier area may be reduced ∼34% by AD 2100.

1. Introduction

Climate change induces complex responses to the Earth's cryosphere (Bamber and Payne, 2004). Monitoring of present changes in mass balance and length

* Corresponding author. Department of Earth Science, University of Bergen, Allégaten 41, N-5007 Bergen, Norway.
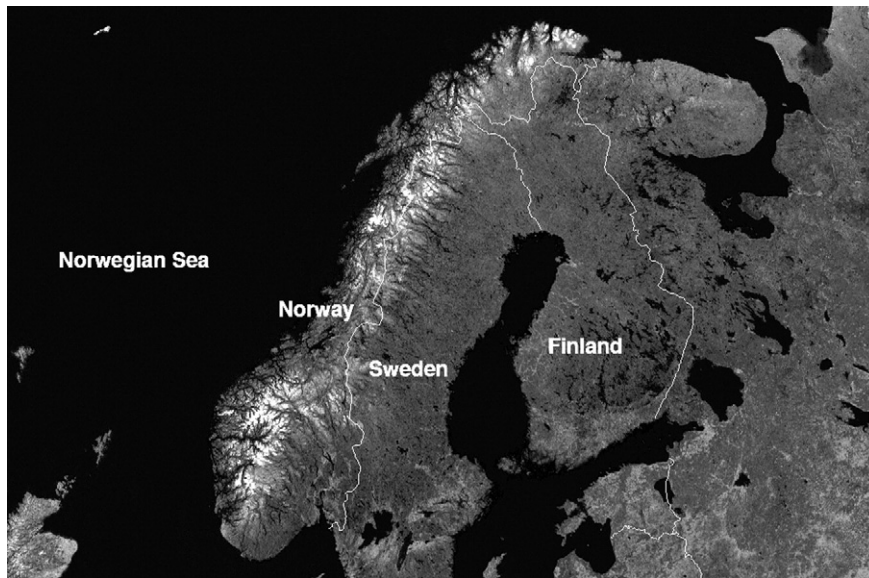*E-mail address:* atle.nesje@geo.uib.no (A. Nesje).

Fig. 1. Satellite image (from NASA World Wind) of Scandinavia. The largest glaciers in Fig. 2 are seen as white spots on the image.

variations of glaciers in response to a changing climate, in particular winter precipitation and summer temperature, is therefore of major importance (e.g. IPCC, 2001; Dyurgerov, 2003, 2005). Glacier fluctuations in mountain regions have been systematically observed for more than a century in various parts of the world. Glacier length is commonly an easily measured parameter that provides an indirect and filtered signal of climate change. In addition, variations in glacier size are important for water resource management (including water supply and hydro-electric power production), natural hazard assessments, and with respect to community planning for tourism and recreation. Mass balance measurements provide a direct (no time delay) signal of climate change that causes variations in accumulation and ablation. At present, the World Glacier Monitoring Service collects data and maintains a database on glacier mass balance and glacier length variations around the world.

Most glaciers around the world are presently retreating (e.g. Dyurgerov, 2005). Increased water discharge from higher melt rates may lead to an increase in the occurrence of natural hazards in glacier-fed catchments. Frontal variations of mountain glaciers were used by Oerlemans (2005) to provide qualitative support for the rise in global temperatures since the late 19th century. Records of glacier volume (mass balance) variations have considerable potential to support or extend the instrumental records of summer temperature and winter precipitation changes and to cast further light on regional

or worldwide temperature and precipitation changes before the instrumental period (e.g. Dyurgerov, 2003).

The retreat of many glaciers worldwide during the past few decades is regarded as an unambiguous sign of global warming (Dyurgerov and Meier, 2000; Dyurgerov, 2005; Oerlemans, 2005). Because data points on glacier length before the period of continuous, annual measurements are irregularly spaced in time and frontal variations have a component of time lag and are a result of variations of both summer temperature and winter precipitation (e.g. Nesje, 2005), the data are more difficult to handle and interpret than many other proxy archives and data. Despite the fact that glacier retreat is mentioned in many climate change assessments, the number of systematic studies of long glacier length records is rather few. Some glaciers, such as Storglaciären (Sweden), Storbreen and Nigardsbreen (Norway), and the Rhône Glacier and Lower Grindelwald Glacier (Switzerland), have been studied in great detail.

The purpose of the present paper is fourfold; (1) to synthesise available records of Holocene glacier variations in different regions in Norway (Fig. 1) reconstructed from sediments in downstream glacier-fed lakes and stratigraphical sections, (2) to use lichenometrically and historically dated moraines at Jostedalsbreen, in Jotunheimen, at Hardangerjøkulen, and at Folgefonna (Fig. 2) to extend glacier length variations back to their maximum position during the 'Little Ice Age', (3) to synthesise the modern climate–glacier relationship from modern mass balance data in Scandinavia, and
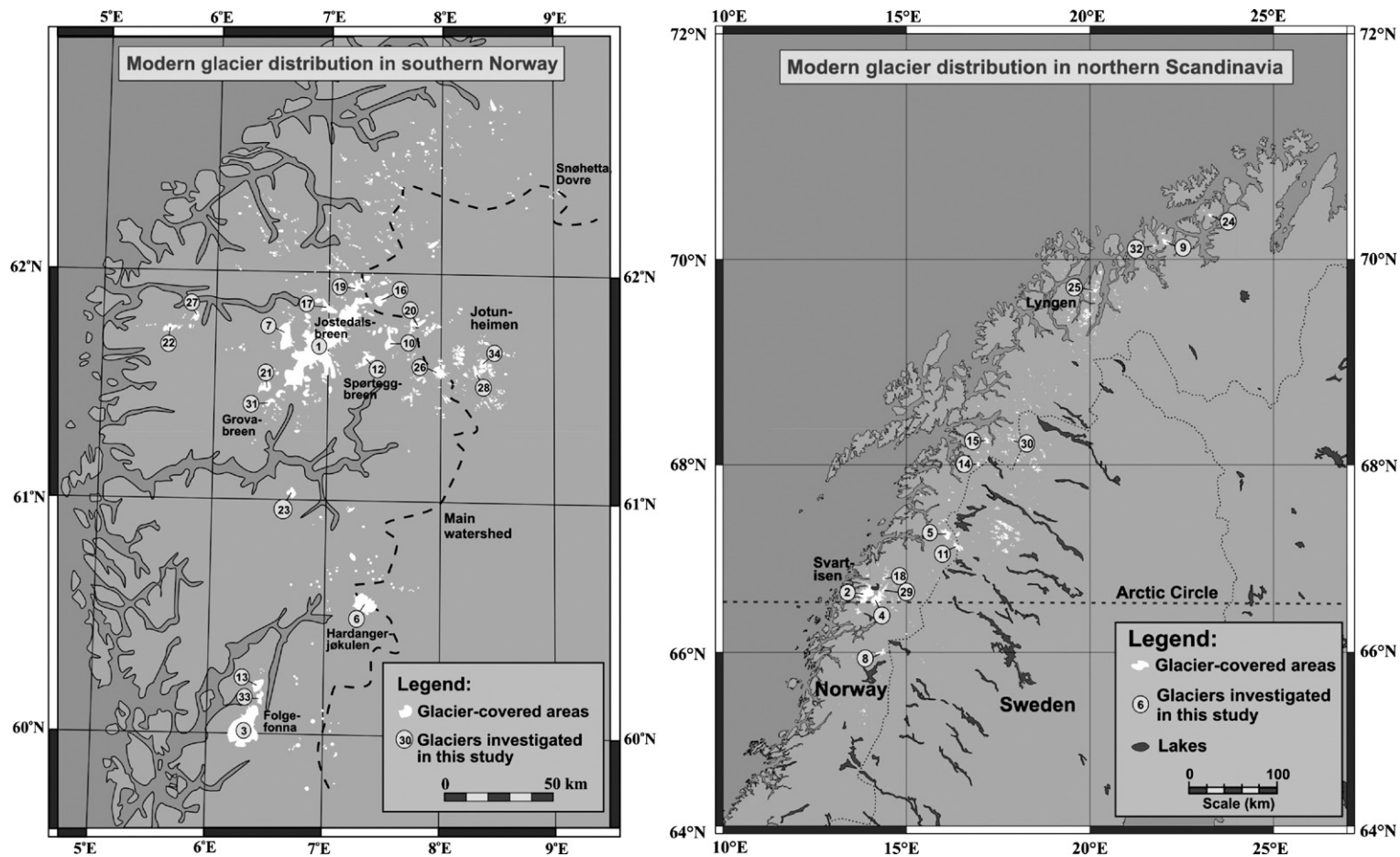
Fig. 2. Location map of glaciers in southern Norway (left) and northern Scandinavia (right). The encircled numbers refer to the glaciers listed in Table 1.
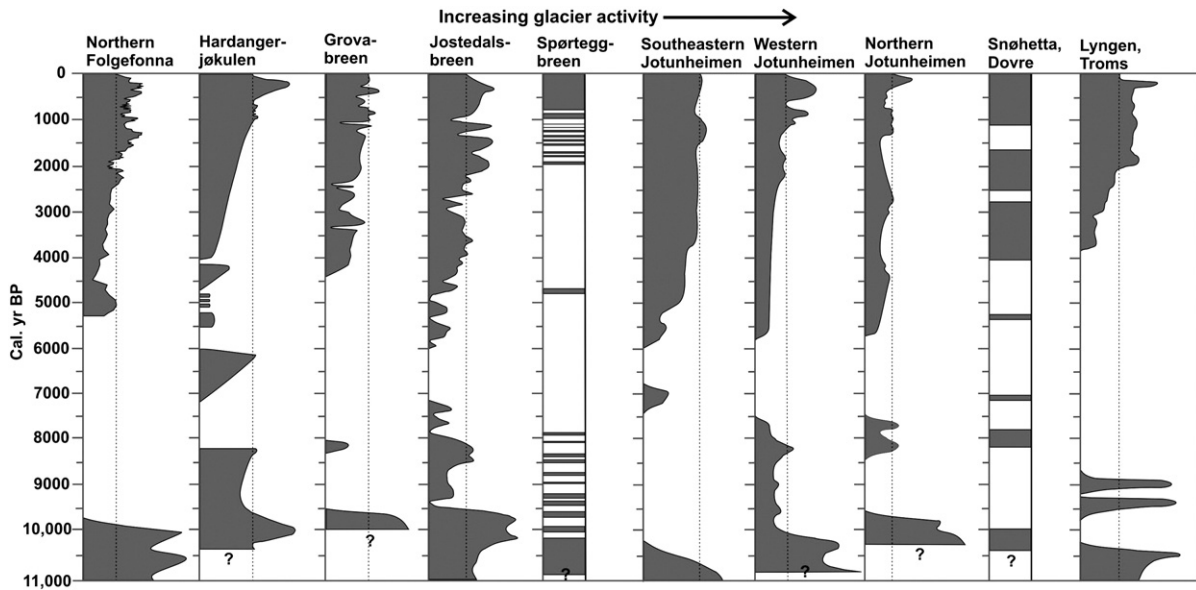
Fig. 3. Holocene glacier variations (horizontal scale is schematic, not to scale) of Norwegian glaciers/glacier regions [Northern Folgefonna (Bakke et al., 2005a,b), Hardangerjøkulen (Dahl and Nesje, 1994, 1996), Grovabreen (Seierstad et al., 2002) Jostedalsbreen (Nesje et al., 2001), Spørteggbreen (Nesje et al., 2006), southeastern Jotunheimen (Lie et al., 2004), western Jotunheimen (Karlén and Matthews, 1992; Matthews and Karlén, 1992), northern Jotunheimen (Matthews et al., 2000, 2005), Snøhetta massif, Dovre (Dahl et al., in prep.), and Lyngen, Troms (Bakke et al., 2005c)]. For location, see Figs. 1 and 2.

(4) present possible effects on the Norwegian glaciers of climate scenarios between 1961–1990 and 2070–2100 presented by the 'RegClim' project (RegClim, 2005).

2. Holocene glacier variations in Norway

The Holocene glacial history of several glaciers in Norway located in both maritime and continental climate regimes in Norway has been reconstructed (e.g. Nesje et al., 1991, 2000a, 2001, 2005, 2006; Karlén and Matthews, 1992; Matthews and Karlén, 1992; Dahl and Nesje, 1994, 1996; Seierstad et al., 2002; Lie et al., 2004; Matthews et al., 2000, 2005; Dahl et al., 2002; Bakke et al., 2005a,b,c; Fig. 3). During the early part of the Holocene outlet fjord/valley glaciers from the Scandinavian ice sheet retreated significantly. This glacial retreat was, however, punctuated by several glacial readvances (Nesje et al., 1991, 2005; Dahl et al., 2002; Bakke et al., 2005a,c). Contiguous sampling at 0.5–1-cm intervals for loss-on-ignition (LOI) analyses of cores from glacier-fed lakes revealed a specific, two-peaked reduction of LOI in the lower part of the cores (Nesje and Dahl, 2001). The reduction in the LOI in glacier-fed lakes mainly reflects increased glacier activity in the catchment, termed the Finse event (Dahl and Nesje, 1994, 1996). The Finse event occurred between ~8500 and 8000 cal. yr BP as a response to

winter precipitation and summer temperature variations around the '8.2 ka event' recorded in the Greenland ice cores, European lake sediments, and in North Atlantic marine records (e.g. Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005). All the studied Norwegian glaciers disappeared for at least some period during the early-/mid-Holocene (subsequent to the Finse Event). During this period the mean summer temperature was in the order of 1.5–2.0 °C warmer than at present (Bjune et al., 2005). The period(s) when the glaciers was (were) melted away was (were) characterised by high summer temperatures and/or low winter precipitation (e.g. Bjune et al., 2005; Nesje et al., 2005). The studied Norwegian glaciers were reformed over the time period from approximately 6000 to 2000 cal. yr BP (Fig. 3). Most Norwegian glaciers experienced their maximum Neoglacial position during the 'Little Ice Age' (e.g. Grove, 1988, 2004). The differences in the glacier variations between the individual glaciers/glacier regions may be due to differences in glacier hypsometry and different response to precipitation and temperature in different climate regions in Norway (see Fig. 7C).

3. 'Little Ice Age' to present glacier variations

Regular measurements of frontal variations were initiated around AD 1900 at some Norwegian glaciers.

Before that the glacier-front positions have been reconstructed from historical evidence and lichenometric dating (e.g. Matthews, 2005). Most Norwegian glaciers retreated during the 20th century (Andreassen et al., 2005). Several periods of advance were, however, recorded since the systematic frontal measurements started in 1899/1900. Several outlet glaciers from maritime ice caps in southern Norway had advances that culminated around AD 1910 and 1930. From the 1930s a significant frontal retreat occurred. In the 1950s maritime glaciers with short response time (<10 yr) started to advance. In the 1990s several of the maritime glaciers started to advance as a response to higher winter accumulation during the first part of the 1990s. Since 2000, on the other hand, most of the observed glaciers have retreated remarkably fast (>100 m annually).

Written documents going back to the 16th century describe catastrophic floods caused by outbursts from glacier-dammed lakes or arable land and farms destroyed by advancing glaciers, for example, during the 18th century in Norway (e.g. Grove, 1988, 2004). A large amount of information is available from documents, sketches, etchings, paintings and old photographs of glaciers. Geomorphologic evidence such as marginal moraines can be used as complementary information to construct the history of glaciers over the last few centuries.

Many glaciers in Norway attained their maximum 'Little Ice Age' position in the mid-18th century. The timing of the maximum 'Little Ice Age' advance of individual glaciers in different parts of southern Norway varied, however, considerably, ranging from the early 18th century to the late 19th century. Reconstructed decadal-

scale 'Little Ice Age' glacier variations in southern Norway do not show consistent regional patterns (Bickerton and Matthews, 1993; Winkler et al., 2003; Matthews, 2005). The regional differences between climate perturbations and glacier response appear to be influenced by differences in the relative importance of summer temperature and winter precipitation operating on different timescales (Nesje et al., 1995, 2001; Nesje and Dahl, 2003; Winkler et al., 2003; Matthews, 2005; Matthews and Briffa, 2005; Nesje, 2005). Data presented from western Norway indicate that the rapid glacier advance in the early 18th century was mainly due to increased winter precipitation rather than lower summer temperatures (Nesje and Dahl, 2003). For example, Nigardsbreen, an eastern outlet glacier from Jostedalsbreen, advanced 2800 m over a 25-yr period between 1710 and 1735, giving a mean annual advance rate of ∼110 m.

In order to reconstruct the cumulative front variations of south Norwegian glaciers since the maximum of the 'Little Ice Age', the distances from the lichenometrically and/or historically dated outer 'Little Ice Age' moraine to the younger moraines and to the modern glacier fronts (glacier position from maps) for 9 outlet glaciers from Jostedalsbreen (Bickerton and Matthews,1993), 16 glaciers in the Jotunheimen region (Matthews, 2005), 2 northern outlet glaciers from Hardangerjøkulen (Andersen and Sollid, 1971), and 6 outlet glaciers from Folgefonna (Tvede, 1972; Bjelland, 1998; Bakke, 1999; Simonsen, 1999; Bakke et al., 2005b) were measured. The frontal variations were then standardised (the maximum 'Little Ice Age' position of the individual glacier was set to 0, whereas the 'modern' position was set to −100). Cumulative glacier length variations of all
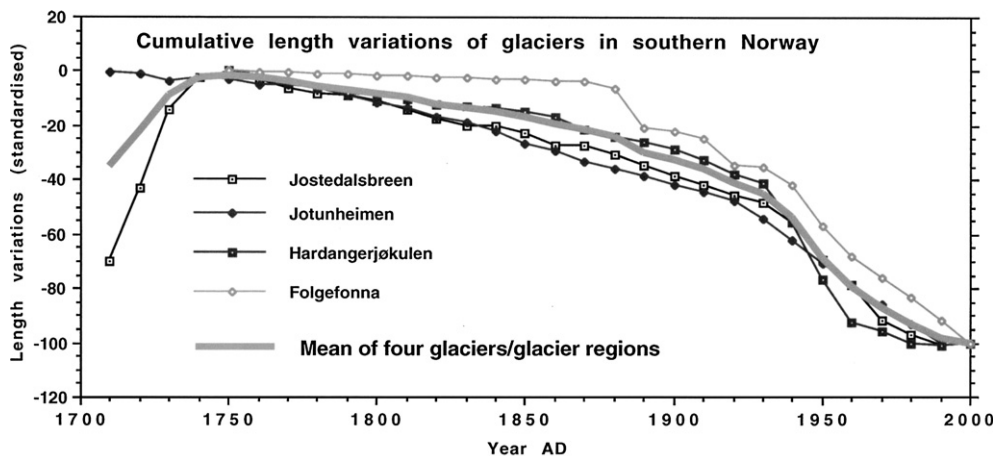

Fig. 4. Mean cumulative glacier length variations (standardised) from the early 18th century to AD 2000 in the four study areas (Jostedalsbreen, Jotunheimen, Hardangerjøkulen, Folgefonna).

glaciers in the four study areas and the mean for the four study areas, presented as standardised values in Fig. 4, show a rather minor but overall retreat from ∼ AD 1750 to 1930s–40s. Subsequently, most Norwegian glaciers retreated significantly. Maritime outlet glaciers with short response time (<10–15 yr) started to advance in the 1950s [for example Briksdalsbreen (Nesje, 2005)]. Outlet glaciers with longer response time (>15–20 yr), however, continued to retreat up to the 1970s (Fig. 5). Several of the smaller maritime glaciers in western Norway started to advance in the early 1990s as a result of higher winter precipitation between 1988/89 and 1994/95 (see Fig. 6D). After 2000 most Norwegian glaciers have retreated remarkably fast (annual frontal retreat >100 m) mainly as a response to high summer temperatures (Andreassen et al., 2005; Nesje, 2005). The age frequency of the marginal moraines at Jostedalsbreen, Breheimen, Jotunheimen, Hardangerjøkulen, and Folgefonna, and in total for all four areas is shown in Fig. 6. The majority of the terminal moraines formed during the 'Little Ice Age' in southern Norway date from AD 1740–50, 1780–90, 1860–70, and 1920–40.

4. The present glaciers in Norway and their relationship to climate

The last glacier inventory in Norway identified 1627 glaciers (Østrem et al., 1988); 714 in southern Norway and 913 in northern Norway (www.nve.no/bre). The glaciers have a total area of 2609 km^2 (approximately 1% of the total area of mainland Norway); 1592 km^2 in southern Norway and 1017 km^2 in northern Norway. The total glacier volume in Norway has been roughly estimated (from a Figure in Østrem et al., 1988 showing

a possible relationship between glacier area and glacier volume) as 164 km^3; 100 and 64 km^3 in southern and northern Norway, respectively. If all glaciers in Norway melt away, the sea level would rise ∼ 0.34 mm. The 1593 glaciers with an area <9 km^2 cover an area of 809 km^2 (31%), whereas the 34 (∼ 2%) largest glaciers in Norway (≥ 9 km^2, Table 1) cover an area of 1800 km^2 (68%). The 1593 glaciers with an area <9 km^2 have an estimated volume of ∼ 51 km^3. Consequently, the 34 largest glaciers in Norway (Table 1) have an estimated volume of ∼ 113 km^3.

The longest, continuous glacier mass balance record in the world is from Storglaciären in northern Sweden (1946-), whereas the next longest continuous mass balance record (1949-) is from Storbreen (Jotunheimen) in central southern Norway (Fig. 7A). Most of the other mass balance records in Norway go back to the early 1960s (Andreassen et al., 2005; Kjøllmoen, 2005). In 2005, mass balance measurements were carried out by the Norwegian Water Resources and Energy Directorate (NVE) at 13 glaciers in Norway, 10 in southern Norway and 3 in northern Norway (www.nve.no/bre). The monitored glaciers in southern Norway provide a west–east transect from the maritime Ålfotbreen with an average accumulation of 3.7 m water equivalents, to the continental Gråsubreen in eastern Jotunheimen with an average accumulation of 0.8 m. For six of the monitored glaciers in southern Norway, there exists a continuous record of 43 yr or more. At Engabreen in northern Norway, the record goes back to 1970. During the last ∼ 45 yr, inland (continental) glaciers have experienced negative mass balance, whereas most of the coastal (maritime) glaciers have a positive mass balance trend, especially in the 1990s (Fig. 7B). The period 1989–1995
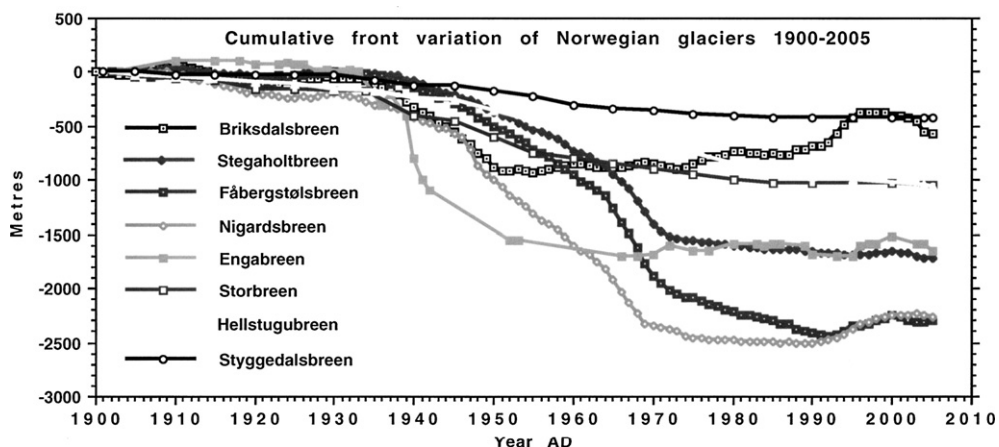

Fig. 5. Cumulative front variations of Norwegian glaciers AD 1900–2005. Data: Andreassen et al., 2005; Kjøllmoen, 2005, updated by NVE.

was characterised by heavy winter precipitation in western Norway resulting in glacier advances of up to 80 m in 1 yr (1993–94 at Briksdalsbreen; Nesje, 2005). The period 2001–2004 was characterised by negative mass balance on the Norwegian glaciers, caused by both low winter accumulation (in 2000–01 and 2002–03) and large summer melting (in 2002 and 2003).

In Scandinavia (including Svalbard), the net mass balance on the maritime glaciers in western Norway is best correlated with the winter balance, whereas the net mass balance on continental glaciers in southern Norway and on the Svalbard glaciers is best correlated with the summer balance (e.g. Nesje et al., 1995, 2000b) (Fig. 7C). This is also reflected in the longer-term cumulative glacier mass balance records (see above). A high positive correlation between the North Atlantic Oscillation (NAO) index (Jones et al., 1997 with later updates) and annual winter and net mass balance on maritime glaciers in Norway has been demonstrated (Nesje et al., 2000b; Reichert et al., 2001; Six et al., 2001), the dominant factor being the strong relationship between precipitation during the accumulation season (October–April) and the NAO winter (December–March) index (Fig. 7D).
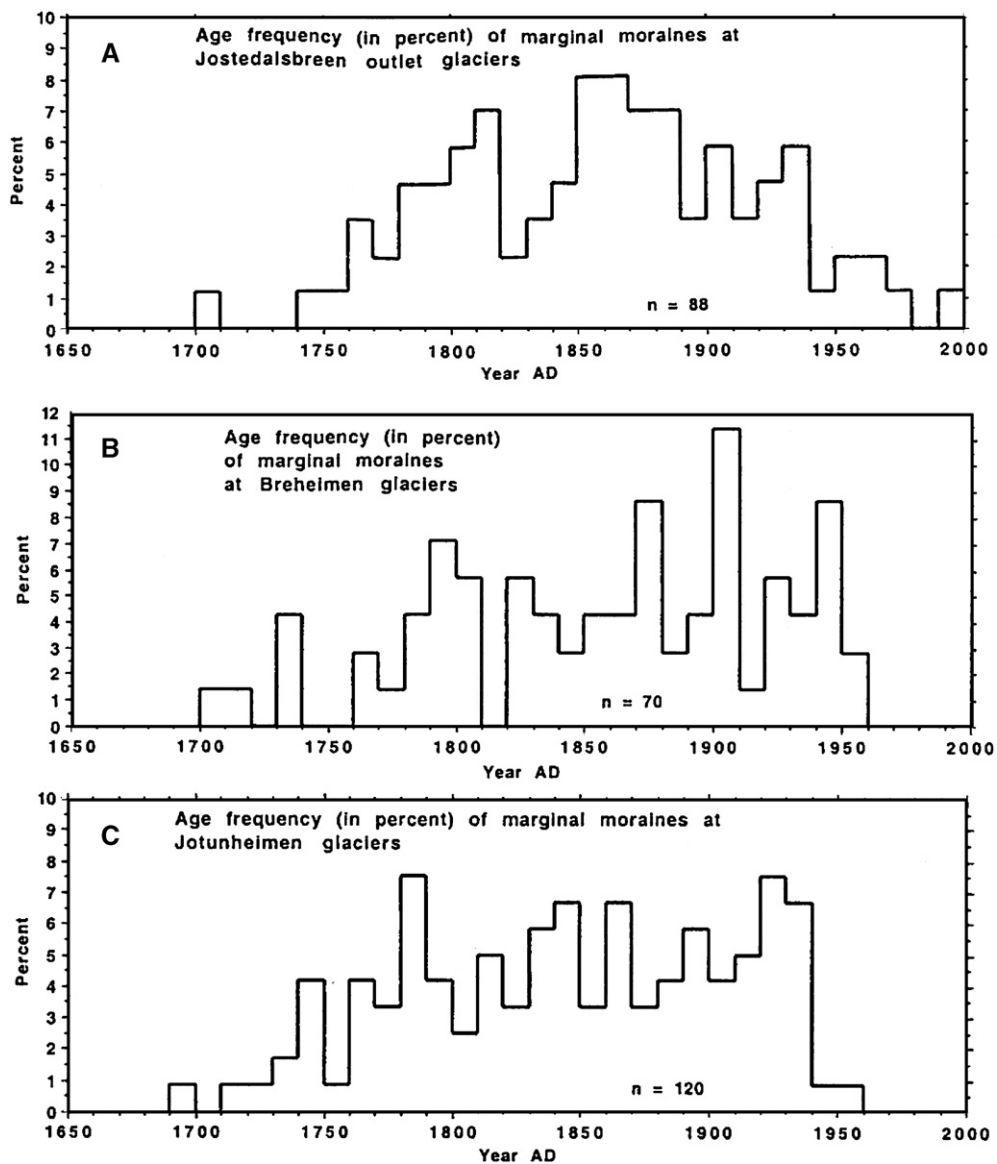

Fig. 6. A) Age frequency (in percent) of marginal moraines at Jostedalsbreen, B) in Breheimen C) in Jotunheimen, D) at Hardangerjøkulen, E) at Folgefonna glaciers, and F) in total in the four study areas. For references, see text.
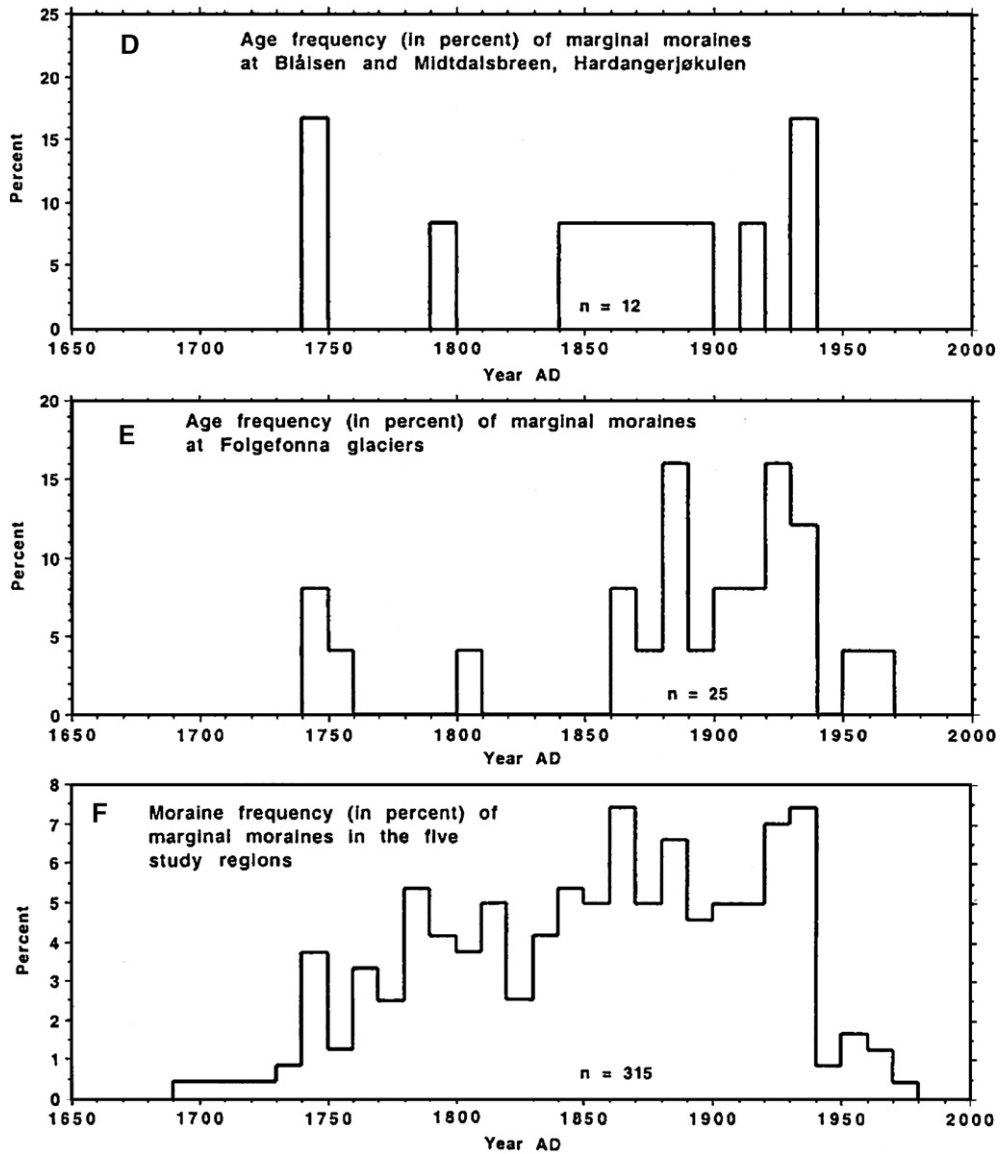
Fig. 6 (*continued*).

By stepwise regression analysis the accumulation, ablation, and equilibrium-line altitude were modelled by circulation indices derived from a gridded monthly mean sea level pressure (MSLP) data set and spring–summer temperature on six south Norwegian glaciers derived from instrumental and proxy data (Nordli et al., 2005). The analyses showed that accumulation on the maritime glaciers was strongly related to western airflow. For the continental glaciers, circulating air in connection with low-pressure systems was also found to be important. Accumulation was better modelled using the MSLP data set than by using the North Atlantic Oscillation index as predictor.

A climate index was generated by combining standardised records of winter (1 October–30 April) precipitation (Pw) and summer (1 May–30 September) temperature (Ts) in Bergen in order to elaborate on the relative importance of summer temperature and winter precipitation on the measured frontal variations of Briksdalsbreen, a western outlet glacier from Jostedalsbreen in western Norway (Nesje, 2005). The standardisation procedure was to subtract the annual values (X) of winter precipitation and summer temperature from the mean value (X_{mean}) for the 1961–1990 climate normal period and divide by the standard deviation (std) of both data sets [$(X - X_{mean})/std$]. The

Table 1

The area, maximum and minimum elevation of the 34 largest (≥ 9 km^2) glaciers in Norway (Østrem et al., 1988). The vulnerability index indicates the least (index = 10) and most (index = 1) vulnerable glaciers to melting away. The index is based on the difference between the maximum elevation of the glacier and the modern steady-state (net mass balance = 0) ELA, and the glacier area of the individual glacier. The glaciers are ranked from the lowest (1) to highest vulnerability (34) to melt away (right-hand column). For location of the individual glacier, see Fig. 2

Name	Area (km^2)	Maximum altitude (m)	Minimum altitude (m)	Vulnerability index	Vulnerability ranking
1. Jostedalsbreen	487	2000	350	10.0	1
2. Vestre Svartisen	221	1580	20	6.2	3
3. Søndre Folgefonna	185	1660	490	7.5	2
4. Østre Svartisen	148	1550	208	5.7	4
5. Blåmannsisen	87	1560	810	4.3	9
6. Hardangerjøkulen	73	1850	1050	2.3	30
7. Myklebustbreen	50	1830	890	4.9	7
8. Okstindbreen	46	1740	750	5.1	6
9. Øksfjordjøkulen	41	1170	330	4.3	11
10. Harbardsbreen	36	1950	1250	3.5	16
11. Salajekna/Sulitjelmaisen	33	1680	830	4.2	13
12. Spørteggbreen	28	1750	1270	2.4	29
13. Nordre Folgefonna	25	1640	990	3.2	22
14. Gihtsejiegna/Giccecokka	25	1500	870	3.1	24
15. Frostisen	25	1710	840	4.2	12
16. Sekkebreen	24	1930	1330	2.9	25
17. Tindefjellbreen	22	1850	940	4.4	8
18. Simlebreen	21	1320	780	3.8	14
19. Tystigbreen	21	1900	1220	3.3	19
20. Holåbreen	20	2020	1320	3.4	18
21. Grovabreen	20	1640	1090	2.6	26
22. Ålfotbreen	17	1380	890	1.7	34
23. Fresvikbreen	15	1660	1270	1.8	33
24. Seilandsjøkulen	14	940	480	2.1	31
25. Strupbreen/Koppangbreen	14	1400	320	5.1	5
26. Smørstabbreen	14	2070	1390	3.2	21
27. Gjegnalundbreen	13	1590	900	3.2	20
28. Hellstugubreen/Vestre Memurubreen	12	2200	1470	3.4	17
29. Bre Beiardalen/(Spidstinden)	12	1560	760	2.6	27
30. Storsteinsfjellbreen	12	1850	930	4.3	10
31. Søndre Jostefonn	11	1620	960	3.1	23
32. Langfjordjøkulen	10	1020	360	2.5	28
33. Midtre Folgefonna	9	1570	1100	2.1	32
34. Veobreen	9	2300	1530	3.6	15

climate index is given by $Pw_{stand} + Ts \, x - 1_{stand}$ (note that Ts must be inverted by multiplying by -1). Pw and Ts may be given equal weight or weighted according to the relative importance of Bw and Bs on Bn in different glacier regions (see Fig. 7C). Following the same procedure as Nesje (2005), climate indices were calculated for western, eastern and northern Norway from regional temperature and precipitation series for Norway 1900–2004 (Hanssen-Bauer, 2005) (Fig. 8A). The climate indices for the different regions were compared with measured net mass balance (data: Kjøllmoen, 2005), yielding correlation coefficients of 0.85 (western Norway/Nigardsbreen), 0.79 (eastern Norway/Gråsubreen), and 0.64 (northern Norway/Engabreen) (Fig. 8B–D).

5. Climate scenario for Norway from AD 1961–1990 to AD 2070–2100 and inferred consequences for Norwegian glaciers and glacier catchments

The RegClim research program (http://regclim.met.no/) provided in 2005 climate scenarios from the period 1961–1990 to 2070–2100 for the entire year and for different seasons for Norway as a whole and for different regions. The climate scenarios, based on the means of the British Hadley Centre (HAD) and the German Max Planck Institute (MPI) model simulations, estimate a rise in the mean summer (ablation season) temperature of 2.3 °C and an increase in the precipitation during the accumulation season (late autumn–winter–early spring) of 16% in western Norway.
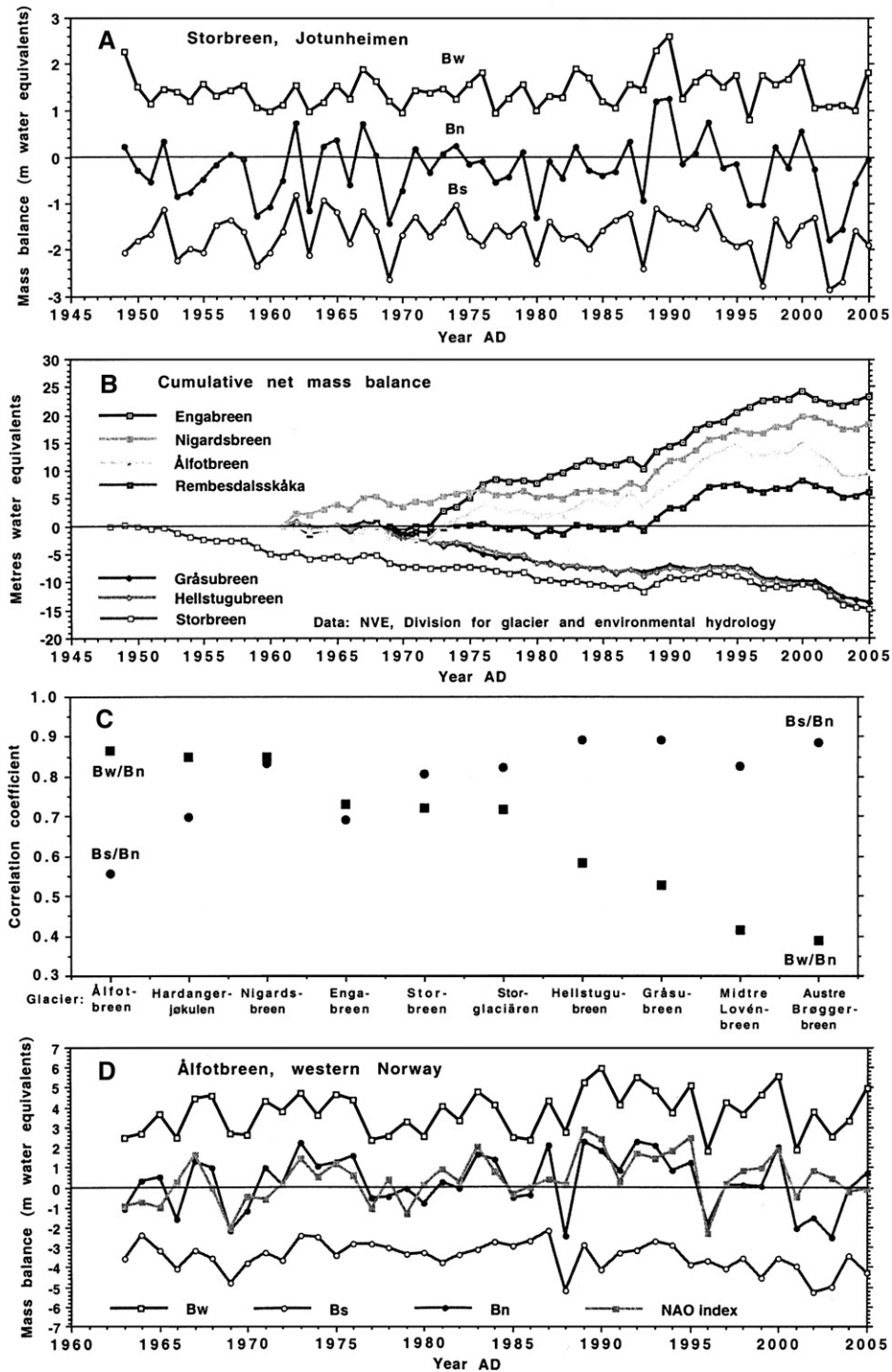
Fig. 7. A) Specific winter (Bw), summer (Bs) and net (Bn) mass balance at Storbreen, Jotunheimen. B) Cumulative specific net mass balance of seven Norwegian glaciers. C) Correlation between winter balance (Bw) and net balance (Bn), and summer balance (Bs) and Bn at Scandinavian (including Svalbard) glaciers (data: Kjøllmoen, 2005). D) Mass balance at Ålfotbreen in western Norway (data: Kjøllmoen, 2005), and the December–March NAO index (Jones et al., 1997, with later updates). The correlation coefficients between NAO/Bw and NAO/Bn at Ålfotbreen are 0.74 and 0.65, respectively.
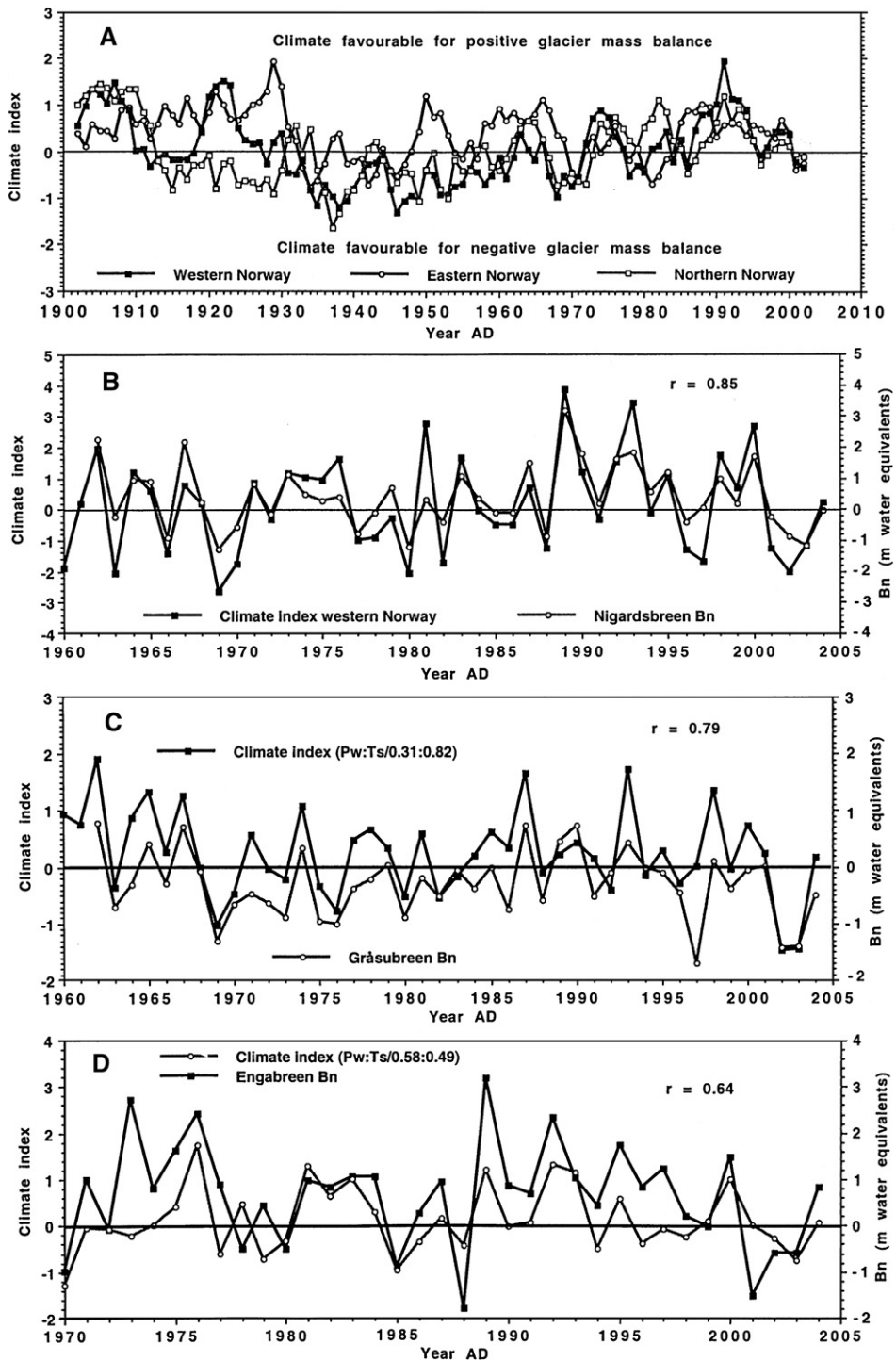
Fig. 8. A) Climate indices for three regions in Norway 1900–2004, indicating periods favourable for positive and negative glacier net mass balance. Summer temperature and winter precipitation are given equal weight. B) The climate index (summer temperature and winter precipitation are given equal weight) for western Norway compared with the net mass balance (Bn) at Nigardsbreen (mass balance data: NVE). C) The climate index for eastern Norway (winter precipitation and summer temperature are weighted 0.31 to 0.82) compared with the net mass balance (Bn) at Gråsubreen, eastern Jotunheimen (mass balance data: NVE). D) The climate index for northern Norway (winter precipitation and summer temperature are weighted 0.58 to 0.49) compared with the net mass balance (Bn) at Engabreen (mass balance data: NVE).
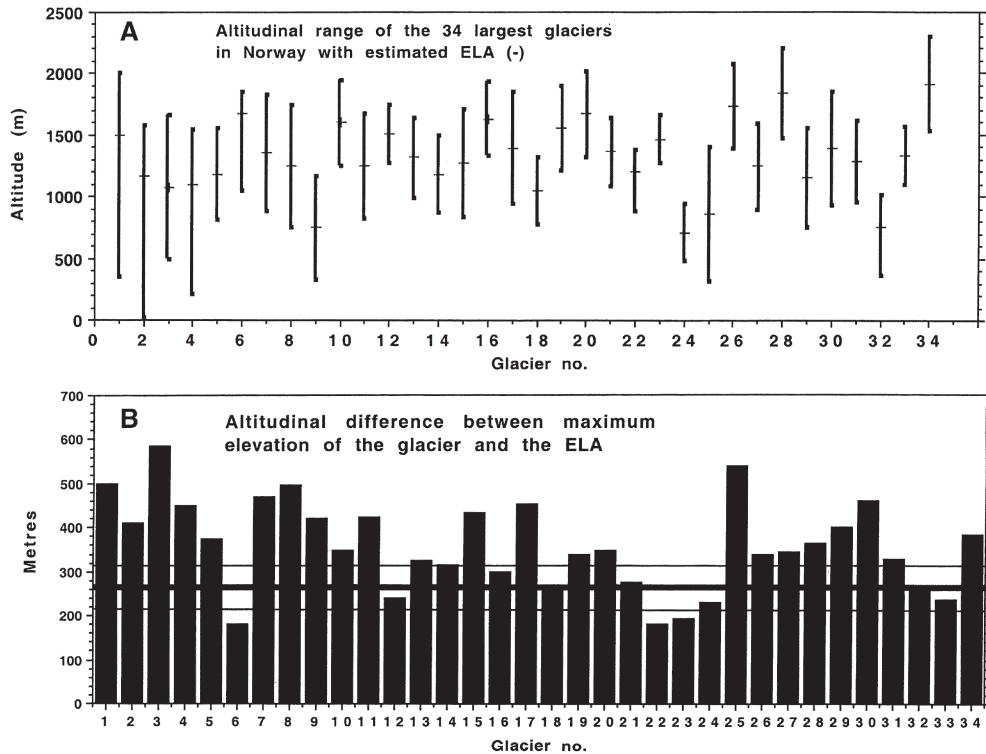
Fig. 9. A) The altitudinal range of the 34 largest (>9 km²) glaciers in Norway with estimated ELA. B) The altitudinal difference between the maximum elevation of the glacier and the ELA of the individual glacier.

An inferred rise of the summer temperature of 2.3 °C and an increase in the winter precipitation of 16% from the period AD 1961–1990 to AD 2070–2100 may cause a net loss of glacier ice corresponding to a melting of ∼140±30 m water equivalents by AD 2100. This has been calculated by using measured winter and summer balances on south Norwegian glaciers (data: Kjøllmoen, 2005) and compared the mass balance values with winter precipitation and summer temperature data from adjacent meteorological stations (data: met.no eKlima).

Putting the climate scenarios into a formula describing a close exponential relationship between ablation-season temperature and accumulation-season precipitation based on the equilibrium-line altitude (ELA) at 10 Norwegian glaciers (Liestøl in Sissons, 1979; Dahl and Nesje, 1992; Lie et al., 2003a,b) yields a rise of the ELA of 260±50 m. A temperature rise of 2.3 °C alone, assuming an environmental lapse rate of 0.65 °C 100 m⁻¹, gives an ELA rise of ∼350 m. The difference of 90 m is due to the ELA lowering caused by increased winter precipitation (accumulation). A higher summer temperature may, however, reduce the length of the accumulation season and thus reduce the amount of snow on the glaciers in the autumn and spring seasons.

The altitudinal range of the 34 largest glaciers in Norway is shown in Fig. 9A, whereas the altitudinal difference between the maximum elevation of the individual glacier and the ELA is indicated in Fig. 9B. The cumulative glacier area in Norway is shown in Fig. 10A, B. A rise of the ELA of 260±50 m will probably cause ∼7 (∼3–11) [∼20 (∼10–33)%] of the 34 largest glaciers in Norway will disappear by AD 2100 (Fig. 11A). The inferred shortening of the accumulation season due to higher spring–autumn temperatures and the lowering of the glacier surface due to increased melting will most likely have a significant effect on the accumulation-area ratio (AAR). The numbers given above may therefore be considered as conservative estimates.

The vulnerability of a glacier to melt away will also depend on a combination of the altitudinal difference between the maximum elevation of the individual glacier and the ELA, and the size of the present glacier (Fig. 11B), as indicated by a 'vulnerability index' (both factors are given equal weight, (Fig. 11C). The less vulnerable glacier to melt away is set to 10, whereas the most vulnerable glaciers to melting away get the lowest numbers. The ten glaciers that are most vulnerable to
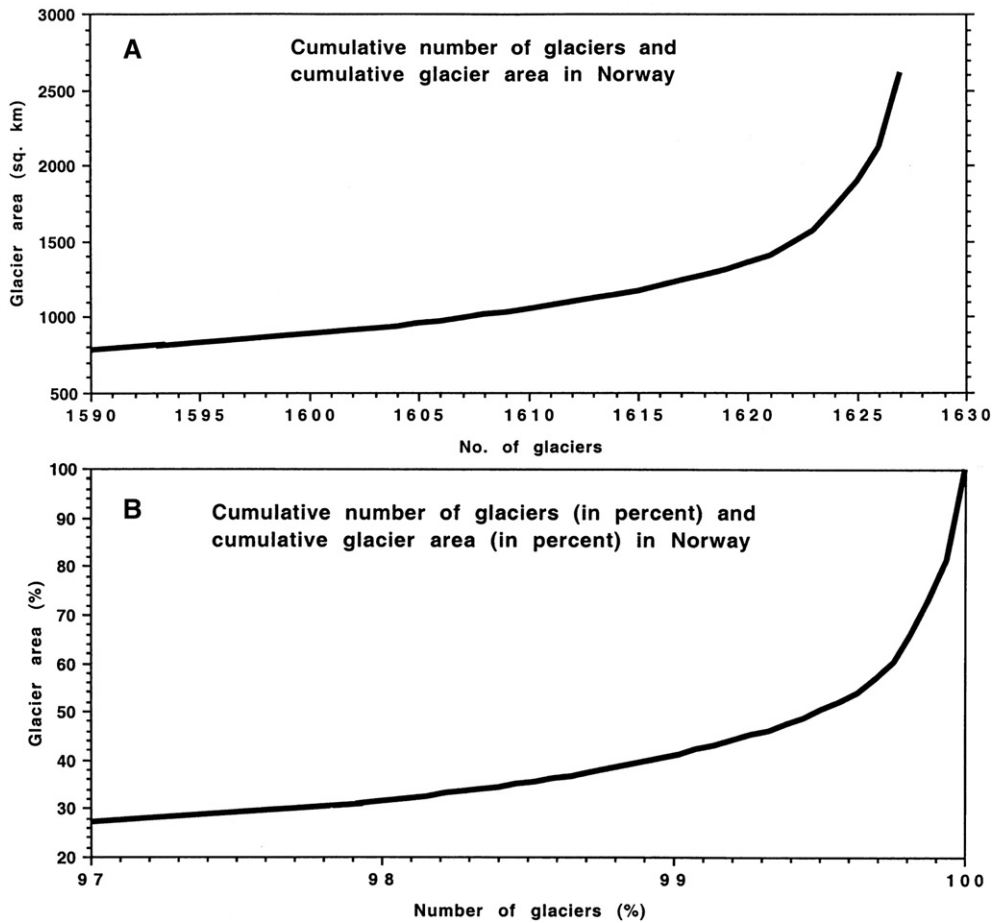
Fig. 10. A) Cumulative glacier area in Norway in km^2 and in percent (B) based on Østrem et al. (1988). Approximately 1600±4 glaciers may melt away with an ELA rise of 260±50 m. The glacier area will be reduced by ∼884 (837–939) km^2. A glacier area of 1725 (1670–1772) km^2 may be left. A melting of ∼98.3 (∼98.1–98.6)% of the Norwegian glaciers may cause a melting of ∼34 (∼32–36)% of the glacier area in Norway.

melt away (of the 34 largest) are ranked in Table 1. As the large glaciers melt away, the majority, if not all, of the smaller glaciers are likely to melt before the larger ones. The number of glaciers are therefore likely to be reduced from 1627 to ∼27 (∼31–23), a reduction of ∼98%, by AD 2100.

The glacier area is likely to be reduced by some 884 km^2 (ca. 34%), from 2609 km^2 (Østrem et al., 1988) to ∼1725 (∼1670–1772) km^2 (66% of the present area). The glacier volume may be reduced by ∼56 (∼53–59) km^3, to ca. 108 (∼105–108) km^3 by AD 2100. If the scenario suggested by RegClim (2005) occurs by AD 2100, this is likely also to have serious consequences for river runoff, water temperature and sediment transport from Norwegian glacier catchments. Hydrologically, this situation may lead to a transient shift. When glaciers disappear from a catchment, the river runoff will be controlled by precipitation as rain in

the snow free season and a peak discharge in the snowmelt season in the spring/early summer. The prolonged high summer river discharge typical of glacierized catchments will not occur when the glaciers are melted.

In Norway 98% of the electricity comes from hydropower and 15% comes from catchments with glaciers. As a large portion of the water discharge in glacier catchments is due to summer melting, most of the river runoff (up to ∼80%) occurs during the summer. In dry and warm summers, the glacier melting maintains this high water discharge. The summer of 2002 was extraordinarily warm in Norway. The mean May–September (the ablation season) temperature was 2.1 °C warmer than the 1961–90 mean. This summer may therefore be regarded as an analogue for the future climate scenario presented by RegClim (2005). In southern Norway, data from NVE shows that the glacier
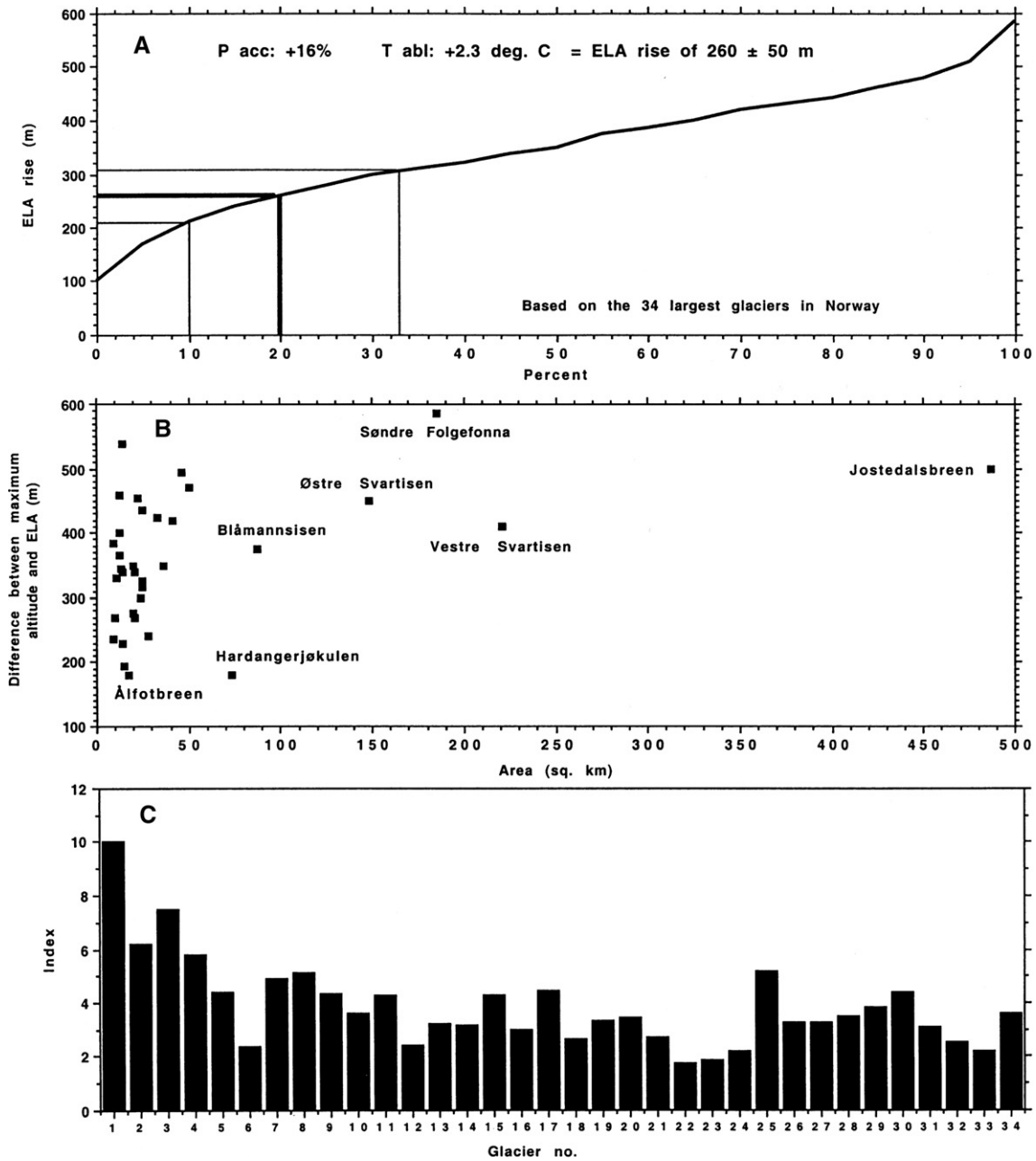
Fig. 11. A) The cumulative difference between the altitudinal difference between the maximum elevation of the glacier and the ELA of the individual glaciers. An ELA rise of 260±50 m and how many of the 34 largest glaciers that may disappear, are indicated. B) The altitudinal difference between the maximum elevation of the glacier and the ELA plotted against the area of the 34 largest glaciers in Norway. C) An index indicating the vulnerability (high number indicates low vulnerability) for the 34 largest glaciers in Norway to melt away. The numbers (1–34) refer to the glaciers listed in Table 1.

melting was 50–100% larger than normal. The glaciers in Jotunheimen had in particular larger than normal melting. The warm and dry summer led to extremely low discharge in rivers with no glaciers in their catchment. In contrast, the Nigardsbreen river in

Jostedalen, where 75% of the catchment is covered by glaciers, experienced a discharge equivalent to an intermediate river flood during most of August. Large river discharge commonly causes large sediment transport. In the river at the margin of Nigardsbreen

Fig. 12. Briksdalsbreen, a western outlet glacier from Jostedalsbreen, has retreated 300 m between 1997, when it was located at the outlet of the lake, and July 2006. Photo: Atle Nesje.

the average concentration of suspended material was 254 mg l^{-1} for the entire summer season. In the two preceding years, the concentration was 20% and 33% of this, respectively. The maximum peak concentration of suspended material was more than 2500 mg l^{-1}. In 2002 approximately 23,000 tons were deposited on the delta at the inlet of Nigardsbrevatnet. This is about twice as much as in a normal year (data: NVE).

When glaciers disappear from a catchment, most or all of the last winter snow melts during the following summer. The annual discharge therefore equals the annual precipitation. When glaciers melt rapidly, local storage of water bodies dammed by ice or till/ glaciofluvial material may cause sudden outburst floods or jökulhlaups, such as at Søndre Folgefonna in 2002 and at Flatbreen in Fjærland in 2004.

6. The future glacier development in the context of the past

In the early Holocene most glaciers in southern Norway melted away rapidly (Fig. 3) due to higher summer temperatures as a result of increased summer solar insolation to the northern Hemisphere and/or lower winter precipitation than at present. Jostedalsbreen melted away about 7600 cal. yr BP (Nesje et al., 2001). The mean summer temperatures were at that time approximately 0.7 °C warmer than at present for

several centuries (Bjune et al., 2005), whereas winter precipitation values were close to those at present (1961–90 mean). Hardangerjøkulen melted away around 8000 cal. yr BP (Dahl and Nesje, 1994, 1996). The mean summer temperatures at that time were ca. 1 °C higher than at present, whereas the winter precipitation was reduced to 80% of the modern. Folgefonna, on the other hand, melted away 9700 cal. yr BP (Bakke et al., 2005a) in a period with summer temperatures similar to those at present and winter precipitation reduced to 70% of the modern. Finally, Svartisen melted away approximately 9800 cal. yr BP (Bakke et al., in prep.). The summer temperatures at that time were about 1 °C warmer than at present and the winter precipitation was reduced to 50% of the 1961–90 mean (Bjune et al., 2005). The reconstructions of Holocene glacier fluctuations in Norway thus indicate that it is quite realistic that glaciers may disappear within a hundred years or so if summer temperatures rise 2–3 °C and if the rise in summer temperature is not compensated by high winter accumulation. Recently, Briksdalsbreen, a western outlet glacier from Jostedalsbreen, retreated ca. 250 m between 1997 and 2005 and ∼6 million m^3 of ice melted at the lower part of the glacier tongue during the same time span (Fig. 12). The lake across which the glacier retreated is rather shallow and apparently did not affect the rate of retreat significantly.

7. Conclusions

1. All the studied glaciers in Norway melted away at least once during the early-/mid-Holocene. The differences between the individual glaciers/glacier regions may be due to differences in glacier hypsometry and different response to winter precipitation and summer temperature in maritime and continental climate regimes.

2. The maximum 'Little Ice Age' glacial extent in different parts of southern Norway varied considerably, from the early 18th century to the late 19th century. Cumulative length variations of glaciers in southern Norway show a general retreat from ∼ AD 1750 to the 1930s–40s. Thereafter, most Norwegian glaciers retreated more rapidly. In the mid-1950s, short maritime outlet glaciers started to advance. However, outlet glaciers with longer frontal time lag (> 15–20 yr) continued to recede until the 1980s. In the 1990s, on the other hand, several of the maritime glaciers in western Norway with short response time (< 10–15 yr) started to advance due to higher winter accumulation from the balance year 1988/89 and during the first part of the 1990s. After 2000 most Norwegian glaciers have retreated significantly (annual frontal retreat of more than 100 m at some glaciers) mainly as a response to high ablation-season temperatures.

3. According to the last Norwegian glacier inventory (Østrem et al., 1988), there are ∼ 1627 glaciers (714 and 913 in southern and northern Norway, respectively), covering an area of 2609 km^2 (about 1% of the total land area of Norway). The total glacier volume in Norway is estimated at 164 km^3.

4. A climate scenario for the period 2071–2100 (RegClim, 2005) is likely to cause a net loss of glacier ice corresponding to a melting of a surface layer of 140 ± 30 m water equivalents by AD 2100 and a rise of the mean ELA of 260 ± 50 m. Consequently, 7 (3–11) [20 (10–33)%] of the 34 largest glaciers in Norway may melt away by AD 2100 and the number of glaciers may thus be reduced from 1627 to ∼ 27 (∼ 31–23), a reduction of ∼ 98%, by AD 2100. The glacier area is likely to be reduced by some 884 km^2 (ca. 34%), from 2609 km^2 to ∼ 1725 (∼ 1670–1772) km^2 (66% of the modern area). The glacier volume may therefore be reduced by ∼ 56 (∼ 53–59) km^3, to ca. 108 (∼ 105–108) km^3 by AD 2100.

Acknowledgements

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