Quaternary Science Reviews 284 (2022) 107501

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A reconstruction of Jostedalsbreen during the Little Ice Age and geometric changes to outlet glaciers since then

Jonathan L. Carrivick [a,*], Liss M. Andreassen [b], Atle Nesje [c], Jacob C. Yde [d]

[a] School of Geography and Water@leeds, University of Leeds, Leeds, UK
[b] Section for Glaciers, Ice and Snow, Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway
[c] Department of Earth Science, University of Bergen, Bergen, Norway
[d] Department of Environmental Sciences, Western Norway University of Applied Sciences, Sogndal, Norway

ARTICLE INFO

Article history:
Received 14 January 2022
Received in revised form
24 March 2022
Accepted 29 March 2022
Available online 6 April 2022

Handling Editor: C. O'Cofaigh

Keywords:
Little Ice Age
Glacier
Mass balance
Norway
Glacier area
Glacier volume

ABSTRACT

Mountain glaciers and ice caps are undergoing rapid mass loss but rates of present-day changes and models of future projections both lack long-term (centennial-scale) context. Here, we reconstruct the maximum glacier extent and ice surface of Jostedalsbreen, which is the largest ice mass in mainland Europe, during the Little Ice Age (LIA) ~ 1740 to 1860. The LIA maximum ice-covered area was 568 km^2 and the LIA ice volume was between 61 km^3 and 91 km^3. We show that the major outlet glaciers have lost at least 110 km^2 or 19% of their LIA area and 14 km^3 or 18% of their LIA volume until 2006. The largest proportional changes for individual outlet glaciers are associated with the loss of ice falls and consequent disconnection of tributaries. Glacier-specific hypsometry changes suggest a mean rise in ELA of 135 m but there is wide inter-glacier variability. A median date for the LIA of 1755 suggests that the long-term rate of ice mass loss has been 0.05 m w.e. a^{-1}. That long-term rate is virtually the same as modern rates, which contrasts with findings of other studies around the world reporting acceleration of glacier mass loss rates since the LIA. Overall, we highlight the utility of geomorphological-based reconstructions of glaciers for understanding and quantifying long-term (centennial-scale) responses to climate and hence for understanding of meltwater production and proglacial landscape evolution.

1. Introduction

Knowledge and understanding of the past extent and ice volume of mountain glaciers and ice caps are of great utility for establishing a baseline and context to the present widespread rapid ice mass loss experienced globally. It is common-practice to calibrate mountain glacier evolution models by 'spinning up' from a previous known ice extent to that of the present day, before having relative confidence in those models to project future changes. Future changes to mountain glaciers and ice caps can therefore only be fully understood with recourse to quantitative understanding of past glacier evolution.

Jostedalsbreen, which is the largest ice cap in mainland Europe (458 km^2 in 2019; Andreassen et al., 2022), has receded and thinned significantly since its Little Ice Age (LIA) maximum (e.g., Grove, 2004) and this trend is only expected to continue with increasing pace in the future due to climate warming (Oerlemans, 1997; Laumann and Nesje, 2009; Hanssen-Bauer, 2017). Several studies have mapped and dated LIA moraines in front of the major outlet glaciers of Jostedalsbreen using lichenometry and historical information (e.g., Mottershead and Colin, 1976; Erikstad and Sollid, 1986; Bickerton and Matthews, 1992, 1993; Nesje, 1994, 2009; Nussbaumer et al., 2011). However, these previous studies have not provided digital outlines of the LIA extent of glaciers for Jostedalsbreen, no area or volume changes have been reported, and no rates of change have been suggested.

The aims of this study are therefore to reconstruct the extent of Jostedalsbreen during the LIA and to calculate the geometric changes to its outlet glaciers since then. We present digital outlines of the maximum LIA extent of Jostedalsbreen glaciers and estimate volume changes and mean rates of ice loss between the LIA and 2006.

1.1. Study area

Jostedalsbreen ice cap is located in the NE part of the Vestland

* Corresponding author.
E-mail address: j.l.carrivick@leeds.ac.uk (J.L. Carrivick).

https://doi.org/10.1016/j.quascirev.2022.107501

county of western Norway, in the eastern inner fjord region (Fig. 1). It has been mapped in several glacier inventories using aerial imagery from 1966 (Østrem and Ziegler, 1969), aerial imagery from 1984 (Østrem et al., 1988), Landsat images from 2006 (Andreassen et al., 2012; Paul et al., 2011) and Sentinel-2 satellite images from 2019 (Andreassen et al., 2021). Whereas the first two inventories were analogue, the later satellite-based inventories have provided digital glacier outlines and digital ice divides. Glacier outlines from 1966 have also been digitised based on first edition topographical 1:50,000 maps (Winsvold et al., 2014). These inventories divide Jostedalsbreen differently and so the number of glacier units and ice divides vary. In the two last inventories >80 glacier units (Andreassen et al., 2012, 2022) are identified and ~20 major outlet glaciers that descend from the ice cap into the surrounding valleys were delineated (see review by Winkler, 2021). The maximum elevation of Jostedalsbreen is ~2000 m asl., while minimum elevation is 413 m asl. at Austerdalsbreen (outline 2019; Andreassen et al., 2022). Glacier thickness to a maximum of 571 m has been measured in several campaigns (e.g. Østrem et al., 1976; Sætrang and Wold, 1986) and has been used to model the ice thickness of Jostedalsbreen (Andreassen et al., 2015).

The climate of the Jostedalsbreen region can be characterized by a strong precipitation gradient from ~2000 mm a^{-1} in the west to ~1000 mm a^{-1} in the east. Mean annual air temperatures are +5 °C and −3 °C for valley floors and the ice cap plateau, respectively. These data are based on 1 km gridded SeNorge maps (1971−2000/2020) interpolated from weather station data and do not accommodate mountain valley-specific micro-climates (c.f. Engelhardt et al., 2012; Hanssen-Bauer, 2017; Lussana et al., 2019).

Geomorphological evidence and sedimentary records show that Jostedalsbreen had its largest Neoglacial extent during the LIA (Nesje et al., 1991, 2008a,b; Nesje and Dahl, 2003). The exact timing of the LIA maximum may have varied from outlet glacier to outlet glacier depending on size, hypsometry, and local climate (Bickerton and Matthews, 1993; Winkler, 2021), but historical documentation from the mid-18th century evidences a glacier advance around the time of LIA maximum from Brenndalsbreen on the west side of Jostedalsbreen (Nesje, 1994) and from Nigardsbreen on the east side (Rekstad, 1904; Grove and Battagel, 1983). The LIA advance at Jostedalsbreen consisted of a single, major advance towards the LIA maximum, followed by a general retreat, interrupted by short-lived (up to a decade) stillstands or re-advances. Most glacier forelands around Jostedalsbreen contain a series of moraines between the LIA moraine and the present glacier terminus.

The age of moraine ridges has been estimated using lichenometric dating curves Erikstad and Sollid (1986); Bickerton and Matthews, (1992, 1993), and these studies indicate that the largest and most distinct moraine ridges within the glacier forelands were formed in the 1870s. After *c.* 1900, glacier length variations have been measured for several outlet glaciers and those records at Fåbergstølsbreen, Nigardsbreen, Austerdalsbreen, and Stigaholtbreen are nearly continuous (Andreassen et al., 2005, 2020). Additionally, Bødalsbreen, Bergsetbreen, Bøyabreen and Briksdalsbreen have a long series of glacier length observations, but

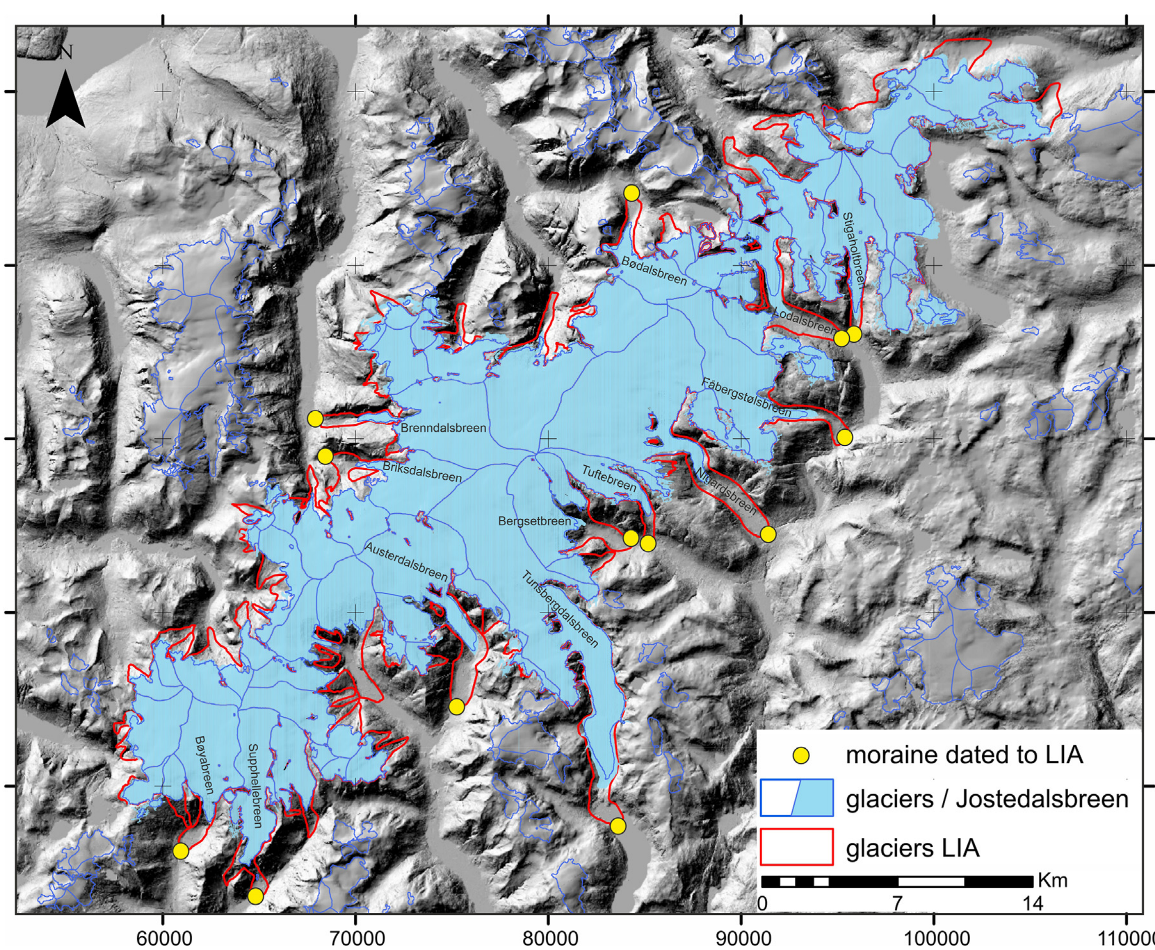

Fig. 1. Overview of Jostedalsbreen glaciers 2006 from Andreassen et al. (2012), outlet glaciers with moraines dated to the LIA labelled and listed in Table 1 and LIA glacier extents mapped in this study. Grid coordinates are UTM 33N projection.

these recently halted due to changes of the glacier terminus hindering accurate measurements (Andreassen et al., 2020).

Periods with glacier terminus advance and moraine formation were recorded around 1910, around 1930, and in the second half of the 1970s (Østrem et al., 1976; Nesje, 1989; Winkler, 1996; Imhof et al., 2011). The most recent advance was caused by decadal-scale increase in winter precipitation in the 1990s resulting in significant glacier advances that culminated around 2000 (Nesje et al., 1995; Andreassen et al., 2005; Nesje, 2005; Nesje and Matthews, 2011). Since mid-2000s, Jostedalsbreen glacier termini have retreated with only a few exceptions (Andreassen et al., 2020; Kjøllmoen et al., 2020).

2. Datasets and methods

2.1. Little Ice Age glacier extent mapping

LIA glacier extents were mapped in this study by extending the digital 2006 outlines from Andreassen et al. (2012) (and as available in GLIMS RGI 6.0) down-valley to the crests of LIA terminal moraines, and then along lateral moraine crests and along trimlines (Fig. 2). Moraines were mapped primarily using a hillshaded image of 1 m gridded digital detrain model (DTM) derived from airborne LiDAR surveyed in August 2020 and downloaded from hoydedata.no (Terratec, 2020; Fig. 3A). Trimlines were identified primarily in sub-metre resolution aerial photograph 'base imagery' in ArcGIS 10.6.2 (Fig. 3B). Our personal knowledge of the valleys assisted these interpretations, but we also conducted a thorough literature review. Moraines dated in the literature (Table 1) were mapped first, then with this understanding contiguous moraines in neighbouring valleys were identified. In the few instances where (undated) moraines ridges were complex, i.e. with multiple concentric crests, we always chose the innermost moraine crest to maintain consistency, permitting replicability, and to provide a conservative estimate of LIA glacier extent and hence a minimum LIA volume and mass. Our area and volume change estimates are also conservative because we did not map LIA outlines for high elevation plateau glacier ice where geomorphological evidence was absent or ambiguous (e.g., at Austdalsbreen).

2.2. LIA ice surface reconstruction

Whilst we trace trimlines to an altitude where they intersect modern day glacier outlines, we need an automated method for extracting elevations not only on these trimlines but also across the glacier surface at that elevation to delimit it as the maximum height at which surface lowering has apparently occurred; below this elevation is the LIA ablation area. Therefore, for each of our LIA outlines, LIA ablation zones were delineated by calculating areas below the LIA equilibrium line altitude (ELA). Glacier specific LIA ELAs were defined using the Area-Altitude Balance Ratio (AABR) method, automated using code developed by Pellitero et al. (2015). We specified a BR (balance ratio) of 1.5 as suggested by Rea (2009) for Norwegian glaciers. The area below each LIA ELA was then extracted in an automated fashion, as described by Carrivick et al. (2019, 2020) and Lee et al. (2021). The vertices of each ablation area were converted to points to enable extraction of elevations of terminal and lateral moraine crests and of the ELA from the 1 m DTM. A surface was interpolated between those points to represent the LIA glacier surface (Fig. 3C). Calculating the difference between our LIA surface and the year 2020 DTM indicated the surface lowering that has occurred since the LIA (Fig. 3D). We then converted that to a glacier-specific volume change and a mean annual rate of change.

Fig. 2. Densely gullied LIA lateral moraine at Fåbergstølsbreen (A) and Austerdalsbreen (B). The trimline associated with the elevation of the moraine crest (indicated by black arrow) also continues across the scree in the distance (A) and across bedrock (B). At least two lower and younger moraine ridges and trimlines are also evident at Austerdalsbreen (B). Both photographs courtesy of Jakob Abermann and taken in autumn 2021.

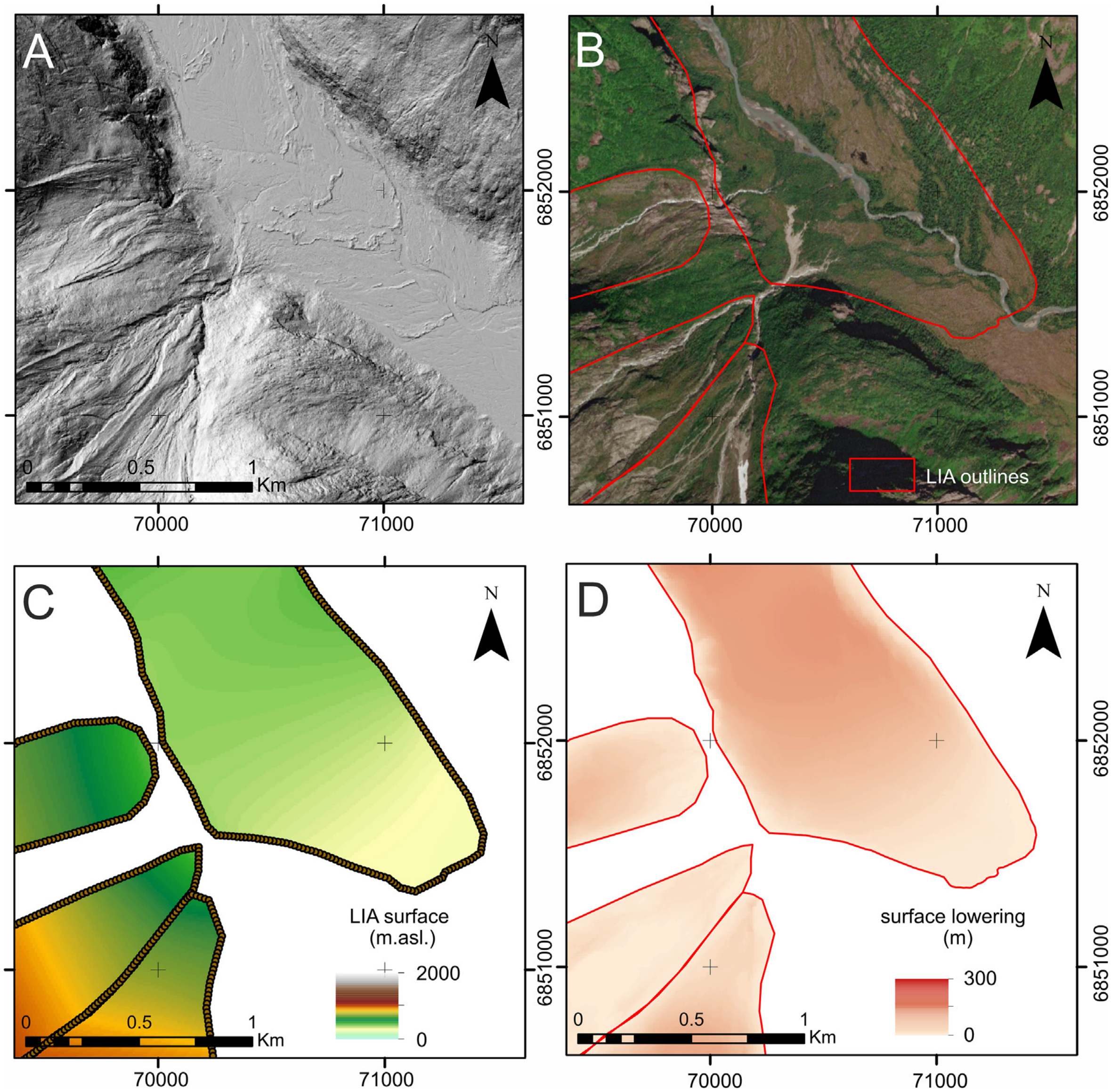

Fig. 3. Illustration of spatial analysis method to interpret geomorphological evidence of LIA glacier extent in the Langedalsbreen valley, including moraines and trimlines, on a 1m resolution airborne LiDAR-generated digital terrain model (DTM) (A) and in sub-metre resolution aerial photograph 'base imagery' in ArcGIS 10.6.2 (B). The extent outlines are converted to vertices/points and elevations extracted from the digital terrain model to these points and then interpolated using Natural Neighbour algorithm to generate an estimate of the former glacier surface (C). The difference between this estimate of a LIA surface and contemporary DTM suggests surface lowering and hence a volume loss (D). Grid coordinates are UTM 33N projection.

2.2.1. Ice volume

To create a glacier bed topography representative of that during the LIA, we removed present day ice from the DTM and also major lakes/reservoirs using 25 m resolution ice thickness data from Farinotti et al. (2019) and bathymetry charts (nve.no), respectively. As glaciers have retreated the lakes are filling with sediment (e.g., Østrem et al., 2005; Kennie et al., 2010; Bogen et al., 2014). We could not account for sediment infill, so our LIA volume estimate is a conservative one. The difference between our LIA surface and our LIA bed topography determined our LIA thickness grid and hence our LIA volume estimate per outlet glacier.

Present day ice volume for each glacier were obtained from both processing of the Farinotti et al. (2019) ice thickness datasets and also from Andreassen et al. (2015). Both these datasets use the same year 2006 glacier outlines with total glacier area of 429.5 km^2 as inputs and there is an excellent agreement; $r^2 = 0.987$, between the glacier-specific volumes suggested by each. To be absolutely clear, the volume change in Table 2 is thus not a function of the surface lowering (modelled LIA surface minus 2020 DTM) but rather a product of the LIA (absolute) volume and the 2006 (absolute) volume estimates.

2.2.2. Uncertainty and rates of change

Uncertainty in area estimates arises from DTM resolution, LIA moraine identification and digitising precision. Our LIA area estimates are subject to low uncertainty due to them being acutely visible both on the hillshaded DTM (1 m) and on sub-metre resolution aerial photographs (Fig. 3A and B). The interpretation of trimlines on the aerial photographs are subjective but a matter of expert judgement and facilitated by observing subtle surface texture differences (sediment drift), apexes of fans on collapsing moraine veneer on hillslopes, vegetation texture changes, and the

Table 1
LIA-dated outer moraines for Jostedalsbreen outlet glaciers from Winkler (2021 and references therein). Note that in our opinion it is very likely that the 1860 date for Stigaholtbreen is in fact from the "1873" moraine because there are only a few moraines in front of Stigaholtbreen.

Local ID	Longitude	Latitude	Glacier name	Dates for LIA moraines	Dating method
2327	6.93	61.62	Austerdalsbreen	1760/65	Lichenometry
2318	7.04	61.66	Bergsetbreen	1750/60	Lichenometry
2273	7.14	61.76	Bødalsbreen	1745/55	Lichenometry
2349	6.76	61.53	Bøyabreen	c. 1750	Lichenometry
2305	6.96	61.69	Brenndalsbreen	1743	Historical observation
2316	6.92	61.66	Briksdalsbreen	c. 1760	Lichenometry
2289	7.20	61.74	Fåbergstølsbreen	1740/50	Lichenometry
2266	7.19	61.78	Lodalsbreen	1825/30	Lichenometry
2297	7.10	61.72	Nigardsbreen	1748	Historical observation
2480	7.31	61.81	Stigaholtbreen	1860?	Lichenometry
2352	6.80	61.53	Supphellebreen	c. 1750	Historical observation
2308	7.09	61.68	Tuftebreen	1770/75	Lichenometry
2320	7.00	61.65	Tunsbergdalsbreen	1748 (1750?) c	Lichenometry
Median				1755	
Range				1740 to 1860	

relative colour of 'fresh' versus 'old' bedrock surfaces. Nevertheless, in the vast majority of cases the geomorphological evidence of LIA ice extent around Jostedalsbreen is clearly distinctive and so we contend our uncertainty in LIA glacier area <10% and substantially better than this in valleys with dated moraines.

The effect of choice of interpolation method on volume calculations in this workflow is also small (Carrivick et al., 2019, 2020; Lee et al., 2021). Our uncertainty in volume arises from the use of a modelled ice thickness and hence bed topography and a modelled LIA ice surface. We are aware that our workflow necessarily creates a simplified LIA ice surface that does not consider longitudinal curvature; rather simply joining moraines crests across valleys, and so following the uncertainty analysis of this workflow conducted by Carrivick et al. (2019, 2020) and Lee et al. (2021), specifically considering DEM resolution, moraine or trimline detection/digitising uncertainty and interpolation method, we consider the uncertainty in our volume estimates to be at worst 20%

Our estimates of rates of change do not depend so much on volume estimate, but rather are largely affected by the choice of a date for the LIA. Dates for LIA moraines around Jostedalsbreen (Table 1; Bickerton and Matthews, 1993) vary between 1740 and 1860, with a mean of 1767 and a median of 1755. We focussed on 1755 for our calculations because the median is a better descriptor of the central tendency of a skewed dataset, but we also report the rates using the earliest and latest dates. We do not know the age of undated moraine ridges in neighbouring valleys but on the basis of the geomorphological evidence (Fig. 2A and B) we assume we can accurately identify those that are contiguous. We acknowledge that rates of glacier mass loss may have varied between the time of the LIA maximum and the present. Episodes of Jostedalsbreen glacier advances have occurred between the 1960s and 1990s but these cannot be accounted for in this study; we merely compute the long-term (centennial-scale) mean rate of change.

For the purposes of comparing our centennial-scale volume changes to present day changes reported in the literature, and for evaluating the relative importance of Jostedalsbreen to water runoff, we converted our volume changes into mass changes. For this calculation, we used a density conversion factor of 850 ± 60 kg/m^3 that is appropriate for a wide range of conditions (Huss, 2013).

3. Results

Many outlet glaciers of Jostedalsbreen were composed of multiple tributary glaciers coalescing to a single outlet/terminus during the LIA. Since then, considerable terminus recession has resulted in extensive fragmentation and so there are more glaciers now than during the LIA. otal glacier area of Jostedalsbreen has reduced from 568 km^2 (±10%) during the LIA to 475 km^2 in 2006; i.e. by 93 km^2 or 16%, and to 458 km^2 in 2019, i.e. by 110 km^2 or 19%. Total glacier volume of Jostedalsbreen has declined from between 76 km^3 (±20% or between 61 km^3 and 91 km^3) during the LIA to 62 km^3 in 2006, i.e. by 14 km^3 or 18%. This area and volume loss is dominated by the near-complete disappearance of long narrow valley glacier tongues, especially those formerly draining westwards. In contrast there has only been a partial loss of valley glacier tongues that drain eastwards (Fig. 4A). Based on this change in hypsometry, the glacier-specific ELA has risen by a mean of 135 m for the 30 largest glaciers (Table 2). Whilst there is high variability in ELA rise between glaciers, a semi-coherent spatial pattern can be discerned whereby the greatest rises have apparently occurred in the central part of Jostedalsbreen (Fig. 4B). Wary of the ± 20% uncertainty in our ice volume, the total mass loss of Jostedalsbreen between the LIA and 2006 is estimated at between 9 Gt and 15 Gt. The mean mass balance between the LIA and 2006 was between 0.04 and 0.08 m w.e. a^{-1} using the earliest (1740) and the latest (1860) date for the LIA, respectively. The mean mass balance for the whole of Jostedalsbreen has been 0.05 m w.e. a^{-1} if the median date of 1755 is used for the LIA. The pattern of glacier-specific mean mass balance since the LIA is very similar to that of volume change as depicted in Fig. 4B.

4. Discussion

Jostedalsbreen outlet glaciers have receded, thinned, and fragmented since the LIA. Recession of glacier termini of the order of several kilometres (>4 km for Nigardsbreen) has revealed expanses of proglacial landscape, composed predominantly of braided river sediments, moraine, exposed bedrock and lakes and rivers (Fig. 2). Quite considerable variability in proglacial landscape composition and functioning can be expected despite similar glacier character behaviour (c.f. Carrivick and Rushmer, 2009), especially where there are outburst floods (e.g. Staines et al., 2015; Guan et al., 2016), such as from Supphellebreen/Flatbreen, Marabreen and Tunsbergdalsbreen (Jackson and Ragulina, 2014; Carrivick and Tweed, 2016).

Glacier thinning has revealed trimlines (Fig. 2) and destabilised lateral moraine to form gullies within that sediment and small debris cones and fans. This formation of a proglacial landscape since the LIA delimits (Carrivick et al., 2018) a relatively young, unstable, and rapidly changing (paraglacial) environment

Table 2
Glacier-specific metrics of LIA and present day (2006) areas (A_), volumes (V_), and changes between those times. Only the largest 30 LIA glaciers are listed for brevity. There is not sufficient evidence at Austdalsbreen to enable a reconstruction of LIA ice extent.

Glacier name	Local ID	Longitude	Latitude	A_LIA (km^2)	A_2006 (km^2)	A_change (km^2)	A_change (%)	V_LIA (km^3)	V_2006 (km^3)	V_change (km^3)	V_change (%)	ELA_LIA (m asl.)	ELA_2006 (m asl.)	ELA_change (m)	Mass change (Gt)	rate from 1755 (m w.e. a^{-1})
Tunsbergdalsbreen	2320	7.00	61.65	52.7	47.5	5.2	10	11.5	10.5	1.0	8.7	1244	1356	−112	0.85	0.064
Nigardsbreen	2297	7.10	61.72	49.1	41.9	7.2	15	8.8	7.6	1.2	13.6	1323	1531	−208	1.02	0.081
Fåbergstølsbreen	2289	7.20	61.74	23.3	20.2	3.1	13	3.9	3.5	0.4	11.2	1425	1515	−90	0.37	0.063
Brenndalsbreen	2305	6.96	61.69	23.2	20.0	3.2	14	3.9	3.7	0.3	6.6	1474	1682	−208	0.22	0.037
Austerdalsbreen	2327	6.93	61.62	30.4	19.8	10.6	35	4.6	3.2	1.4	30.7	1231	1457	−226	1.19	0.153
Kjenndalsbreen	2296	7.03	61.71	21.2	19.0	2.2	11	3.3	3.1	0.3	8.4	1488	1640	−152	0.24	0.044
Bøyabreen	2349	6.76	61.53	15.8	13.8	2.0	13	2.9	2.7	0.1	4.4	1303	1495	−192	0.11	0.027
Supphellebreen	2352	6.80	61.53	15.3	12.8	2.5	16	2.4	2.3	0.1	3.7	1212	1408	−196	0.08	0.020
Stigaholtbreen	2480	7.31	61.81	13.5	12.5	1.1	8	2.1	2.0	0.1	7.0	1362	1418	−56	0.13	0.037
Briksdalsbreen	2316	6.92	61.66	22.4	11.7	10.7	48	2.6	1.7	0.9	34.4	1411	1622	−211	0.76	0.134
Bergsetbreen	2318	7.04	61.66	18.8	11.1	7.7	41	2.2	1.4	0.8	36.6	1337	1583	−246	0.68	0.142
Krunebreen	2280	7.10	61.74	11.5	10.8	0.7	6	1.6	1.5	0.1	7.4	1567	1634	−67	0.10	0.034
Austdalsbreen	2478	7.34	61.83		10.3				1.6				1420			
Erdalsbreen	2481	7.27	61.80	15.9	10.3	5.7	36	1.8	1.3	0.5	26.1	1353	1440	−87	0.39	0.096
Langedalsbreen	2329	6.87	61.61	27.2	9.3	17.9	66	3.2	1.2	2.0	62.8	1249	1610	−361	1.70	0.244
Lodalsbreen	2266	7.19	61.78	24.3	9.3	15.0	62	2.7	0.8	1.9	70.2	1298	1426	−128	1.62	0.262
Lundabreen	2348	6.72	61.53	10.2	8.9	1.3	13	1.2	1.1	0.1	7.4	1406	1496	−90	0.08	0.030
Sikilbreen	2457	7.40	61.87	12.3	8.5	3.8	31	1.3	1.0	0.4	26.7	1387	1574	−187	0.30	0.096
Bødalsbreen	2273	7.14	61.76	10.0	8.4	1.6	16	1.3	1.1	0.2	14.2	1418	1576	−158	0.16	0.062
Opptaksbreen	2347	6.84	61.55	9.5	7.7	1.8	19	1.2	1.1	0.1	7.9	1300	1443	−143	0.08	0.032
Sygneskarsbreen	2461	7.35	61.85	7.5	7.5	0.0	0	1.2	1.0	0.3	21.4	1458	1539	−81	0.22	0.115
Vetle Supphellebreen	2355	6.84	61.53	8.4	7.3	1.1	13	0.9	0.8	0.1	7.7	1276	1369	−93	0.06	0.026
Tuftebreen	2308	7.09	61.68	7.9	6.8	1.1	14	0.9	0.8	0.1	10.5	1376	1523	−147	0.08	0.040
Melkevollbreen	2324	6.83	61.62	7.5	6.6	1.0	13	0.9	0.8	0.1	9.7	1458	1587	−129	0.07	0.037
Ruteflotbreen	2294	6.94	61.71	7.8	6.0	1.8	23	0.5	0.4	0.1	19.8	1400	1571	−171	0.09	0.047
Tverrbyttnbreen	2459	7.46	61.86	5.9	3.6	2.4	39.9	0.4	0.2	0.1	40.4	1452	1547	−95	0.12	0.082
Vesledalsbreen	2474	7.28	61.83	5.2	3.4	1.8	33.9	0.3	0.2	0.1	28.5	1316	1421	−105	0.07	0.051
Nystølsbreen	2361	6.91	61.52	4.4	3.1	1.3	29.5	0.3	0.2	0.1	20.7	1282	1442	−160	0.05	0.042
Sygneskarsbreen	2471	7.36	61.84	3.1	3.1	0.0	0.3	0.3	0.3	0.0	0.7	1488	1488	0	0.00	0.002
None	2328	6.99	61.62	3.6	2.8	0.9	24.1	0.2	0.2	0.0	14.6	1465	1585	−120	0.03	0.029
Marabreen	2364	6.71	61.51	2.9	2.5	0.3	12.1	0.2	0.2	0.0	21.8	1320	1303	17	0.04	0.052

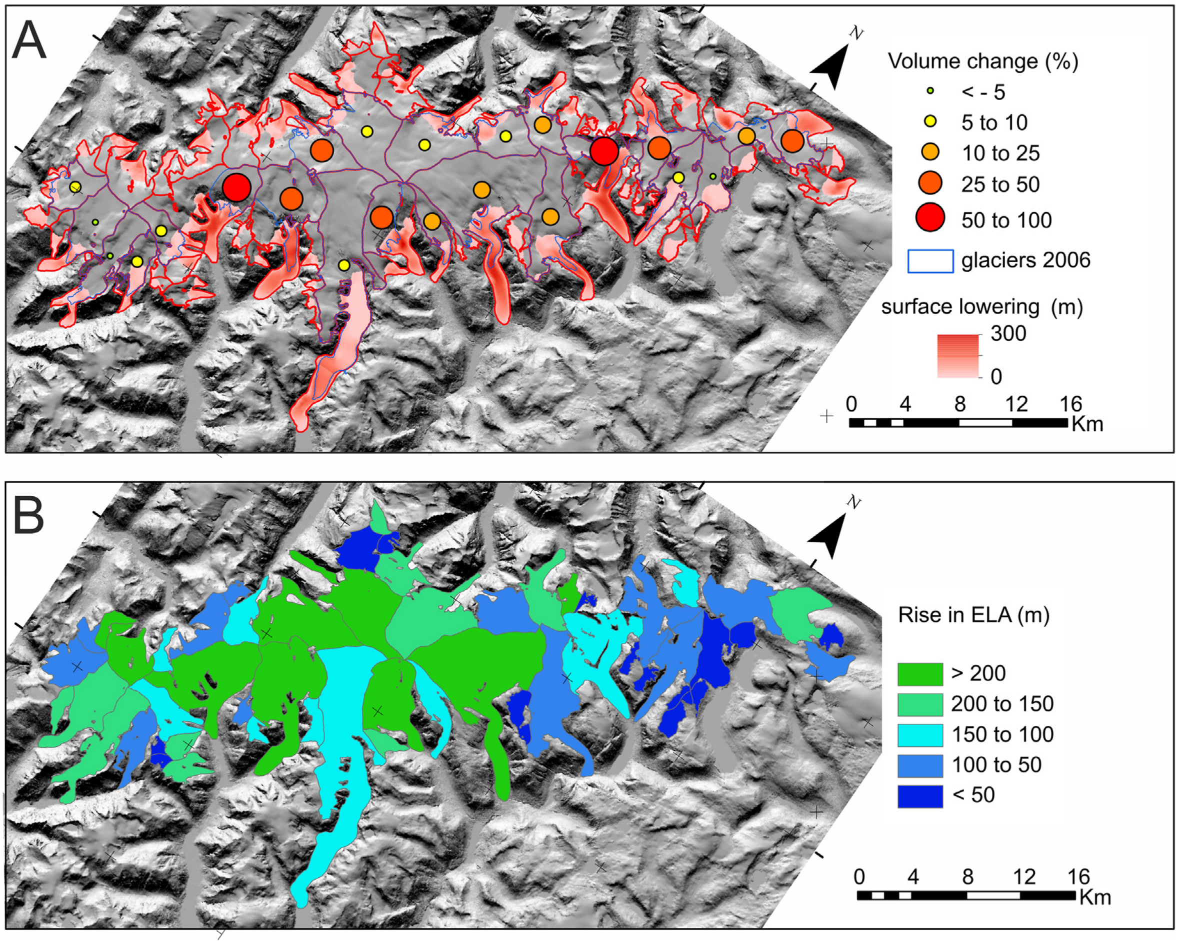

Fig. 4. Surface lowering in ablation areas of LIA Jostedalsbreen outlet glaciers between the LIA and 2006 and estimated glacier-specific volume changes as a percentage of the LIA total (A). Glacier-specific ELA changes calculated from the change in glacier hypsometry between the LIA and 2006 have been largest for the largest glaciers in the central part of Jostedalsbreen (B). For clarity volume changes for only the 30 largest glaciers are depicted in panel A.

(Carrivick and Heckmann, 2017). Proglacial sediment sources, pathways and sinks as well as the bulk catchment-aggregated sediment yield must be understood for water resources, hazard management and natural habitats and ecosystems (Carrivick and Tweed, 2021).Alpine river ecosystems are mostly determined by channel stability (controlling bedload and suspended sediment) and water temperature (e.g. Carrivick et al., 2012; Brown et al., 2015; Fell et al., 2017), both of which are attenuated with distance from a glacier terminus and the presence of a proglacial lake.

Fragmentation of glaciers has resulted via separation of tributaries, such as at Bergsetbreen, Lodalsbreen and Briksdalsbreen, and via detachment of ablation areas from accumulation areas, such as is ongoing at Brenndalsbreen, Bøyabreen and Supphellebreen. These morphological changes are common to mountain glaciers but are exacerbated at Jostedalsbreen due to the strong influence of the plateau, and in particular the elevation of the edge of that plateau, on glacier hypsometry, which for Jostedalsbreen outlet glaciers are 'top-heavy' (c.f. the glacier hypsometry equation of Jiskoot et al., 2009). Thus, glaciers with the greatest ELA rise, i.e. those that are apparently most sensitive to regional climate change, have accumulation areas situated in the south and centre of the relatively narrow plateau (Fig. 4B). The complex hypsometry and high mass balance gradients produce outlet glaciers have high inter-annual variability e.g. see example of Nigardsbreen in Rea (2009, his Fig. 6) and so the heterogeneity between ELAs of neighbouring mountain glaciers and ice cap outlet glaciers is not unexpected (c.f. Torsnes et al., 1993; Carrivick and Brewer, 2004; Carrivick and Chase, 2011). The heterogeneityhighlights the difficulty of using moraine ridges in glacier reconstructions on these types of glaciers and the importance of controlling any sampling strategy of glaciers if not working with an inventory-style approach.

In general, larger (during the LIA) glaciers have experienced a greater rate of mass loss (m w.e. a^{-1}) but this relationship is weak ($r^2 = 0.15$). However, the two largest Jostedalsbreen glaciers, Nigardsbreen and Tunsbergdalsbreen skew this relationship considerably and if they are excluded $r^2 = 0.39$. These two glaciers have also had a very different geodetic mass balance from 1964 to 2013; Nigardsbreen was almost in balance whilst Tunsbergdalsbreen experienced a strong surface lowering and mass deficit (Andreassen et al., 2020). The largest glacier volume loss as a percentage of the original volume has occurred at Bergsetbreen and Lodalsbreen, which both have lost entire tributary ice falls (Fig. 4A).

Elsewhere in Norway, reconstructions of LIA glacier size have delivered length and area changes, but volume changes since the LIA or mass balance changes since the LIA have not been reported. In Jotunheimen, which is an alpine area immediately east of Jostedalsbreen and with a more continental climate, a total of 233 mapped mountain glaciers reduced in area by 35% and length 34% from the 1750 to 1800 LIA extent to 2003 (Baumann et al., 2009). For the Hardangerjøkulen, which is Norway's 6th largest ice cap and located to the south of Jostedalsbreen, the glacier area reduced by 37% from 1750 LIA to 2010 (Weber et al., 2019). In Nordland county, glaciers reduced in area by 47% from ~1899 to 1999 (Weber et al., 2020a) but this study has a larger uncertainty (than ours) due to being based on digitising historical maps. In Lyngen, there were two LIA maximum extents, one around 1750 and the most recent LIA maximum culminated in ~1915. The glacier area reduction across Lyngen since the LIA has been ~11% (Stokes et al., 2018) but this change is only from 1915 to 1953 and is only determined for a sample of 18 glaciers although larger glacier area reductions were determined for a larger sample of glaciers. In Northern Troms and Finnmark, Leigh et al., (2020) report area reductions of 39%–1989 for a sample of mountain glaciers that had a LIA maximum dated to 1814 (±41 years). Langfjordjøkelen in Troms and Finnmark, shrank by 57% between 1925 LIA and 2018 (Weber et al., 2020b). Winsvold et al. (2014) estimated from historical maps that the five northernmost ice caps in Troms and Finnmark, were reduced in area from 21 to 91% (Langfjordjøkelen 62%), with a mean area reduction of 57%, from ~1900 to 2006. Later study showed that the historical map extent of Langfjordjøkelen is unrealistic and overestimated, and the 1925 LIA is a better estimate (Weber et al., 2020b). Therefore, whilst there has been considerable variability in the centennial-scale response of glaciers in Norway and with some uncertainties in dates and in mapping accuracies, the Jostedalsbreen region has experienced amongst the smallest reduction in glacierised area of any Norwegian region since the LIA.

Measurements of decadal-scale rates of mass loss only exist for three glaciers of Jostedalsbreen (Nigardsbreen and Tunsbergdalsbreen from 1964 to 2013, Austdalsbreen 1966–2009) and combined is 0.04 m w.e. a^{-1} (Andreassen et al., 2020). That 'modern' rate of mass loss is; slightly less than the long-term (centennial-scale) rate of mass loss of 0.05 m w.e. a^{-1} calculated in this study if the median date for the LIA is taken, the same as the modern rate if the earliest date for the LIA is taken, and double the modern rate if using the latest LIA date. Those three glaciers account for 25% of the Jostedalsbreen area and so assuming that they are representative of the entire ice cap it can be suggested that Jostedalsbreen is unusual in global terms in not evidencing acceleration of glacier mass loss between the LIA and the present day. Indeed, there might possibly be a slow-down in the rate of mass loss. This unexpectedly steady rate of glacier mass loss of Jostedalsbreen since the LIA could be explained by periods of positive mass balance experienced from the 1960s to the 1990s (Nesje et al., 1995; Nesje, 1989; Andreassen et al., 2005, 2020; Winkler, 1996; Imhof et al., 2011), the lattermost (the Briksdalsbre Event) of which has been linked to enhanced winter precipitation (Nesje and Matthews, 2011). Whilst of ELA changes might most casually be used to infer air temperature changes, we cannot know whether precipitation (amount and gradient) has changed between the LIA and modern times. We also note that our volume and mass changes from the LIA to 2006 ignore the last 15 years when glacier mass balances across Norway are becoming increasingly negative (Andreassen et al., 2020).

Studies from several other parts of the world have determined centennial-scale rates of glacier volume and mass loss since the LIA; e.g. for Vatnajökull, Iceland (Hannesdóttir et al., 2015), NE Greenland (Carrivick et al., 2019), Patagonia (Glasser et al., 2011), the Southern Alps, New Zealand (Carrivick et al., 2020) and across the Himalaya (Lee et al., 2021). These studies usually conduct their analysis via an inventory-style approach, as herein, which mitigates problems of sampling bias including glacier size. Focusing on the inventory-style analysis results, and those that have been able to compute mass balance rates, comparison of the LIA to present average rate with modern (decadal-scale rates) shows a 23% acceleration of glacier mass loss in NE Greenland, a doubling of mass loss for the Vatnajökull ice cap, for Patagonia and for the Southern Alps, and a ten-fold increase across the Himalaya. A trivial comparison of these quantities from the few studies across the World might suggest a control of latitude on glacier responses to climate change since the LIA.

5. Conclusions

Reconstructing the former extent and size of glaciers is important for understanding responses of glaciers to climate forcing and unravelling regional and local controls. Geomorphological reconstructions offer a powerful tool to quantify long-term changes to glaciers, especially when time-scales longer than the few decades represented by the satellite era are considered. Estimation of long-term (centennial-scale) rates of change of glaciers give context to modern changes and should inform future projections, as well as being of utility for understanding meltwater production and proglacial landscape evolution.

Jostedalsbreen has lost 19% of its glacierised area and 18% of its volume between the LIA, which was about 1755, and 2006. Glacier-specific terminus retreat of up to 4 km has occurred and ELAs have risen by a mean of 135 m. These proportions of glacier loss are notable for being less than reported for glaciers and ice caps elsewhere in Norway. Greatest proportional losses have occurred for glaciers where ice falls have been lost and thus tributaries disconnected. Accepting that the number of time periods in our study are very few, the mean rate of mass loss of Jostedalsbreen has not apparently changed significantly in the period between the LIA and the present, which is in stark contrast to the findings of studies reporting the decline of glaciers since the LIA elsewhere in the world. Attribution of winter precipitation during the 1960s to the 1990s as the reason for positive mass balances could explain the lack of an acceleration in the rate of mass loss of Jostedalsbreen glaciers from the LIA to the present, in contrast to widespread acceleration reported around the World.

Data availability

Our LIA glacier outlines are available at https://hdl.handle.net/11250/2836938. Our LIA glacier outlines data are also submitted to GLIMS https://www.glims.org/.

Contributions

This study was initiated by JLC. Glacier LIA extents were mapped by JLC with detailed advice and checks by AN. JLC developed the analysis workflow and conducted the data analysis. JLC prepared all the figures. All authors interpreted the results. JLC led the writing of the paper and all authors contributed to writing. Clare Boston and an anonymous reviewer are thanked for their constructive suggestions that improved the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study is a contribution to the JOSTICE project (grant no. 302458) funded by the Research Council of Norway (NFR). Jakob Abermann, Gernot Seier and Thomas Scheiber are thanked for discussions about the LIA geomorphological evidence during field work in September 2021.

References

Andreassen, L.M., Elvehøy, H., Kjøllmoen, B., Engeset, R.V., Haakensen, N., 2005. Glacier mass balance and length variation in Norway. Ann. Glaciol. 42, 317–325.

Andreassen, L.M., Winsvold, S.H., Paul, F., Hausberg, J.E., 2012. Inventory of Norwegian glaciers. NVE Report 28, 236.

Andreassen, L.M., Huss, M., Melvold, K., Elvehøy, H., Winsvold, S.H., 2015. Ice thickness measurements and volume estimates for glaciers in Norway. J. Glaciol. 61, 763–775.

Andreassen, L.M., Elvehøy, H., Kjøllmoen, B., Belart, J.M.C., 2020. Glacier change in Norway since the 1960s – an overview of mass balance, area, length and surface elevation changes. J. Glaciol. 66, 313–328.

Andreassen, L.M., Moholdt, G., Kääb, A., Messerli, A., Nagy, T., Winsvold, S.H., 2021. Monitoring glaciers in mainland Norway and Svalbard using Sentinel. NVE Rapport 3 2021, 94.

Andreassen, L.M., Nagy, T., Kjøllmoen, B., Leigh, J.R., 2022. A Sentinel-2 based inventory of Norway's glaciers and ice-marginal lakes 2018/2019. J. Glaciol. 1, 22. https://doi.org/10.1017/jog.2022.20.

Baumann, S., Winkler, S., Andreassen, L.M., 2009. Mapping glaciers in Jotunheimen, south-Norway, during the 'Little ice age' maximum. Cryosphere 3, 231–243.

Bickerton, R.W., Matthews, J.A., 1992. On the accuracy of lichenometric dates: an assessment based on the 'Little Ice Age' moraine sequence of Nigardsbreen, southern Norway. Holocene 2, 227–237.

Bickerton, R.W., Matthews, J.A., 1993. 'Little Ice Age' variations of outlet glaciers from the Jostedalsbreen ice-cap, southern Norway: a regional lichenometric-dating study of ice-marginal moraine sequences and their climatic significance. J. Quat. Sci. 8, 45–66.

Bogen, J., Xu, M., Kennie, P., 2014. The impact of pro-glacial lakes on downstream sediment delivery in Norway. Earth Surf. Process. Landforms 40, 942–952.

Brown, L.E., Dickson, N.E., Carrivick, J.L., Fuereder, L., 2015. Alpine river ecosystem response to glacial and anthropogenic flow pulses. Freshw. Sci. 34, 1201–1215.

Carrivick, J.L., Brewer, T.R., 2004. Improving local estimations and regional trends of glacier equilibrium line altitudes. Geogr. Ann. Phys. Geogr. 86, 67–79.

Carrivick, J.L., Heckmann, T., 2017. Short-term geomorphological evolution of proglacial systems. Geomorphology 287, 3–28.

Carrivick, J.L., Rushmer, E.L., 2009. Inter-and intra-catchment variations in proglacial geomorphology: an example from Franz Josef glacier and Fox glacier, New Zealand. Arctic Antarct. Alpine Res. 41, 18–36.

Carrivick, J.L., Tweed, F.S., 2016. A global assessment of the societal impacts of glacier outburst floods. Global Planet. Change 144, 1–16.

Carrivick, J.L., Brown, L.E., Hannah, D.M., Turner, A.G., 2012. Numerical modelling of spatio-temporal thermal heterogeneity in a complex river system. J. Hydrol. 414, 491–502.

Carrivick, J.L., Heckmann, T., Turner, A., Fischer, M., 2018. An assessment of landform composition and functioning with the first proglacial systems dataset of the central European Alps. Geomorphology 321, 117–128.

Carrivick, J.L., Boston, C.M., King, O., James, W.H., Quincey, D.J., Smith, M.W., Grimes, M., Evans, J., 2019. Accelerated volume loss in glacier ablation zones of NE Greenland, Little Ice Age to present. Geophys. Res. Lett. 46, 1476–1484.

Carrivick, J.L., James, W.H., Grimes, M., Sutherland, J.L., Lorrey, A.M., 2020. Ice thickness and volume changes across the southern Alps, New Zealand, from the Little ice age to present. Sci. Rep. 10, 1–10.

Carrivick, J.L., Chase, S.E., 2011. Spatial and temporal variability of annual glacier equilibrium line altitudes in the Southern Alps, New Zealand. N. Z. J. Geol. Geophys. 54, 415–429.

Carrivick, J.L., Tweed, F.S., 2021. Deglaciation controls on sediment yield: towards capturing spatio-temporal variability. Earth Sci. Rev. 103809.

Engelhardt, M., Schuler, T.V., Andreassen, L.M., 2012. Evaluation of gridded precipitation for Norway using glacier mass-balance measurements. Geogr. Ann. Phys. Geogr. 94, 501–509.

Erikstad, L., Sollid, J.L., 1986. Neoglaciation in South Norway using lichenometric methods. Norsk Geografisk Tidsskrift - Nor. J. Geogr. 40, 85–105.

Farinotti, D., Huss, M., Fürst, J.J., Landmann, J., Machguth, H., Maussion, F., Pandit, A., 2019. A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nat. Geosci. 12, 168–173.

Fell, S.C., Carrivick, J.L., Brown, L.E., 2017. The multitrophic effects of climate change and glacier retreat in mountain rivers. Bioscience 67, 897–911.

Glasser, N.F., Harrison, S., Jansson, K.N., Anderson, K., Cowley, A., 2011. Global sea-level contribution from the Patagonian icefields since the Little ice age maximum. Nat. Geosci. 4, 303–307.

Grove, J.M., 2004. Little Ice Ages, 2 Volumes. Routledge, London.

Grove, J.M., Battagel, A., 1983. Tax records from western Norway, as an index of Little Ice Age environmental and economic deterioration. Climatic Change 5, 265–282.

Guan, M., Carrivick, J.L., Wright, N.G., Sleigh, P.A., Staines, K.E., 2016. Quantifying the combined effects of multiple extreme floods on river channel geometry and on flood hazards. J. Hydrol. 538, 256–268.

Hannesdóttir, H., Björnsson, H., Pálsson, F., Aðalgeirsdóttir, G., Guðmundsson, S., 2015. Variations of southeast Vatnajökull ice cap (Iceland) 1650–1900 and reconstruction of the glacier surface geometry at the Little Ice Age maximum. Geogr. Ann. Phys. Geogr. 97, 237–264.

Hanssen-Bauer, I. (Ed.), 2017. Climate in Norway 2100 – a Knowledge Base for Climate Adaptation.

Huss, M., 2013. Density assumptions for converting geodetic glacier volume change to mass change. Cryosphere 7, 877–887.

Imhof, P., Nesje, A., Nussbaumer, S.U., 2011. Climate and glacier fluctuations at Jostedalsbreen and Folgefonna, southwestern Norway and in the western Alps from the 'Little ice age' until the present: the influence of the North Atlantic oscillation. Holocene 22, 235–247.

Jackson, M., Ragulina, G., 2014. Inventory of glacier-related hazardous events in Norway. Norges vassdrags-og energidirektorat (NVE)/Rep. - Nor. Water Resour. Energy Dir. 83, 213.

Jiskoot, H., Curran, C.J., Tessler, D.L., Shenton, L.R., 2009. Changes in Clemenceau Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment, length–slope and area–aspect relations. Ann. Glaciol. 50, 133–143.

Kennie, P., Bogen, J., Olsen, H.C., 2010. Estimating long term sediment yields from sediment core analysis. Ann. Warsaw Univ. Life Sci. 42, 115–126.

Kjøllmoen, B., Andreassen, L.M., Elvehøy, H., Jackson, M., 2020. Glaciological Investigations in Norway 2019, NVE Rapport 34-2020. Norwegian Water Resources and Energy Directorate.

Laumann, T., Nesje, A., 2009. The impact of climate change on future frontal variations of Briksdalsbreen, western Norway. J. Glaciol. 55, 789–796.

Lee, E., Carrivick, J.L., Quincey, D.J., Cook, S.J., James, W.H.M., Brown, L.E., 2021. Accelerated mass loss of Himalayan glaciers since the Little ice age. Sci. Rep. 11, 24284.

Leigh, J.R., Stokes, C.R., Evans, D.J.A., Carr, R.J., Andreassen, L.M., 2020. Timing of 'Little Ice Age' maxima and subsequent glacier retreat in northern Troms and western Finnmark, northern Norway. Arctic Antarct. Alpine Res. 52, 281–311.

Lussana, C., Tveito, O.E., Dobler, A., Tunheim, K., 2019. seNorge_2018, daily precipitation, and temperature datasets over Norway. Earth Syst. Sci. Data 11, 1531–1551.

Mottershead, D.N., Colin, R.L., 1976. A study of Flandrian glacier fluctuations in Tunsbergdalen, southern Norway. Norw. J. Geol. 56, 413–436.

Nesje, A., 1989. Glacier-front variations at the outlet glaciers from Jostedalsbreen and climate in the Jostedalsbre region of western Norway in the period 1901–1980. Nor. Geografisk Tidsskr. 43, 3–17.

Nesje, A., 1994. A gloomy 250 year memory: the glacier destruction of the Tungøyane farm in Oldedalen, western Norway, 12 December 1743. Nor. Geografisk Tidsskr. 48, 133–135.

Nesje, A., 2005. Briksdalsbreen in western Norway: AD 1900–2004 frontal fluctuations as a combined effect of variations in winter precipitation and summer temperature. Holocene 15, 1245–1252.

Nesje, A., 2009. Late Pleistocene and Holocene alpine glacier fluctuation in Scandinavia. Quat. Sci. Rev. 28, 2119–2136.

Nesje, A., Dahl, S.O., 2003. The 'Little ice age'—only temperature? Holocene 13, 139–145.

Nesje, A., Matthews, J.A., 2011. The Briksdalsbre event: a winter precipitation-induced decadal-scale glacial advance in southern Norway in the AD 1990s and its implications. Holocene 22, 249–261.

Nesje, A., Kvamme, M., Rye, N., Løvlie, R., 1991. Holocene glacier and climate history of the Jostedalsbreen region, western Norway; evidence from lake sediments and terrestrial deposits. Quat. Sci. Rev. 10, 87–114.

Nesje, A., Johannesen, T., Birks, H.J.B., 1995. Briksdalsbreen, western Norway: climatic effects on the terminal response of a temperate glacier between AD 1901 and 1994. Holocene 5, 343–347.

Nesje, A., Bakke, J., Dahl, S.O., Lie, Ø., Matthews, J.A., 2008a. Norwegian mountain glaciers in the past, present and future. Global Planet. Change 60, 10–27.

Nesje, A., Dahl, S.O., Thun, T., Nordli, Ø., 2008b. The "Little Ice Age" glacial expansion in western Scandinavia: summer temperature or winter precipitation? Clim. Dynam. 30, 789–801.

Nussbaumer, S.U., Nesje, A., Zumbühl, H.Z., 2011. Historical glacier fluctuations of Jostedalsbreen and Folgefonna (southern Norway) reassessed by new pictorial and written evidence. Holocene 21, 455–471.

Oerlemans, J., 1997. A flowline model of Nigardsbreen, Norway: projection of future glacier length based on dynamic calibration with the historic record. Ann. Glaciol. 24, 382–389.

Østrem, G., Ziegler, T., 1969. Atlas over breer i Sør-Norge. Meddelelse nr 20 fra Hydrologisk avdeling. NVE, p. 207.

Østrem, G., Liestøl, O., Wold, B., 1976. Glaciological investigations at Nigardsbreen, Norway. Nor. Geogr. Tidsskr. 30, 187–209.

Østrem, G., Tandberg, K., Selvig, K.D., 1988. Atlas over Breer I Sør-Norge: Atlas of Glaciers in South Norway: Revidert Utgave Utarbeidet På Grunnlag Av Flybilder Tatt I Perioden 1969-1986. Vassdragsdirektoratet.

Østrem, G., Haakensen, N., Olsen, H.C., 2005. Sediment transport, delta growth and sedimentation in lake Nigardsvatn, Norway. Geogr. Ann. Phys. Geogr. 87, 243–258.

Paul, F., Andreassen, L.M., Winsvold, S.H., 2011. A new glacier inventory for the Jostedalsbreen region, Norway, from Landsat TM scenes of 2006 and changes since 1966. Ann. Glaciol. 52, 153–162.

Pellitero, R., Rea, B.R., Spagnolo, M., Bakke, J., Hughes, P., Ivy-Ochs, S., Lukas, S., Ribolini, A., 2015. A GIS tool for automatic calculation of glacier equilibrium-line altitudes. Comput. Geosci. 82, 55–62.

Rea, B.R., 2009. Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions. Quat. Sci. Rev. 28, 237–248.

Rekstad, J., 1904. Fra Jostedalsbræen. Bergens Museums Aarbog, Bergen, 1904 No. 1.

Sætrang, A.C., Wold, B., 1986. Results from the radio echosounding on parts of the Jostedalsbreen ice cap, Norway. Ann. Glaciol. 8, 156–158.

Staines, K.E., Carrivick, J.L., Tweed, F.S., Evans, A.J., Russell, A.J., Jóhannesson, T., Roberts, M., 2015. A multi-dimensional analysis of pro-glacial landscape change at Sólheimajökull, southern Iceland. Earth Surf. Process. Landforms 40, 809–822.

Stokes, C.R., Andreassen, L.M., Champion, M.R., Corner, G.D., 2018. Widespread and accelerating glacier retreat on the Lyngen Peninsula, northern Norway, since their 'Little ice age' maximum. J. Glaciol. 64, 100–118.

Terratec, A.S., 2020. Laserskanning for nasjonal detaljert høydemodell. NDH Jostedalsbreen 2pkt 2020 (hoydedata.no). Terratecprosjektnr: 10047. https://hoydedata.no/LaserInnsyn/ProsjektRapport?filePath=%5C%5Cstatkart.no%5Choydedata_orig%5Cvol10%5C4706%5Cmetadata%5CNDH%20Jostedalsbreen%202pkt%202020_Prosjektrapport.pdf.

Torsnes, I., Rye, N., Nesje, A., 1993. Modern and Little Ice Age equilibrium-line altitudes on outlet valley glaciers from Jostedalsbreen, western Norway: an evaluation of different approaches to their calculation. Arct. Alp. Res. 25, 106–116.

Weber, P., Boston, C.M., Lovell, H., Andreassen, L.M., 2019. Evolution of the Norwegian plateau icefield Hardangerjøkulen since the 'Little ice age. Holocene 29, 1885–1905.

Weber, P., Andreassen, L.M., Boston, C.M., Lovell, H., Kvarteig, S., 2020a. An ~1899 glacier inventory for Nordland, northern Norway, produced from historical maps. J. Glaciol. 66, 259–277.

Weber, P., Lovell, H., Andreassen, L.M., Boston, C.M., 2020b. Reconstructing the Little Ice Age extent of Langfjordjøkelen, northernmost Arctic Norway, as a baseline for assessing centennial-scale icefield recession. Polar Res. 39. https://doi.org/10.33265/polar.v39.4304.

Winkler, S., 1996. Front variations of outlet glaciers from Jostedalsbreen, western Norway, during the twentieth century. Nor. Geol. Unders. Bull. 431, 33–47.

Winkler, S., 2021. Terminal moraine formation processes and geomorphology of glacier forelands at selected outlet glaciers of Jostedalsbreen, South Norway. In: Beylich, A.A. (Ed.), Landscapes and Landforms of Norway. World Geomorphological Landscapes, pp. 33–69.

Winsvold, S.H., Andreassen, L.M., Kienholz, C., 2014. Glacier area and length changes in Norway from repeat inventories. Cryosphere 8, 1885–1903.