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# Interrogating glacier mass balance response to climatic change since the Little Ice Age: reconstructions for the Jotunheimen region, southern Norway

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Developing a long-term understanding of the cryosphere is important in the study of past climatic change. Here we used a nested approach combining diverse instrumental (monthly meteorological data from four weather stations, as well as gridded data) and proxy data (based on blue intensity measurements from local tree ring records) to create a reconstruction of past summer temperature for the central Jotunheimen area in southern Norway. This record was then used to reconstruct annual glacier mass balance from 1962, the start of the yearly measurements, back to 1722, immediately prior to the regional Little Ice Age maximum. Our reconstruction of the 'average' Jotunheimen cumulative glacier mass balance is based on three representative glaciers (Storbreen, Hellstugubreen and Gråsubreen) that were synthesized into one composite record which we term 'Gjennomsnittsbreen' ('mean glacier' in Norwegian) to filter out localized controls on the behaviour of individual glaciers. While not ignoring the role of precipitation on glacier mass balance, our reconstruction demonstrates that glaciers in this region exhibit a strong summer temperature control and appear to have been declining more or less continuously since the mid-18th century. However, it also shows that this long-term trend of overall retreat in Jotunheimen is punctuated by relatively short-lived periods of neutral or occasionally positive glacier mass balance, signifying periods of stillstand or small-scale glacier advance. These periods or 'events' in our reconstruction were compared with an independent record of 12 moraine-building events developed using lichenometry. A minimum of 10 of the moraine-building events identifiable in our reconstruction were also identifiable in the lichenometric data which affords confidence in the performance of our interrogative model. A critical implication of this successful glacier mass balance reconstruction based on just summer temperature is that for Jotunheimen – in contrast to Norwegian maritime glaciers further to the west – there is no need (as was proposed in some previous studies) to invoke large, prolonged increases in winter snowfall to explain glacier advances, not even for events such as the Little Ice Age.

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Mountain glaciers are sensitive indicators of variations in climate. Trends and patterns in precipitation and temperature often lead to measurable changes in glacier geometry and mass balance, which is why 'before-and-after' images of receding glacier fronts are widely used to illustrate the effects of modern climatic change around the globe (Burkhart *et al.* 2017; Christian *et al.* 2018).

On a global scale, the last significant advance of glaciers occurred during the Little Ice Age (LIA), the timing of which was region-dependent, but expressed most strongly between the mid-17th and mid-19th centuries. Some LIA glaciers are even reported to have grown to twice their current size (Wanner *et al.* 2008; Chambers, 2016), but since then the vast majority of mountain glaciers have been retreating dramatically (Grove 2004; Leclercq *et al.* 2014; Roe *et al.* 2016; Solomina *et al.* 2016; Beniston *et al.* 2018). More specifically, while this retreat may initially have been relatively slow and steady, over the 20th century and more recently, the rate of glacial retreat has accelerated globally (Zemp *et al.* 2015; Hugonnet *et al.* 2021). Still, the melting of mountain glaciers is not uniform for all of the world's glaciated regions. For example, in recent decades there have been short-term regional variations in the Karakoram region and in New Zealand, where glaciers have shown periods of growth which may be considered somewhat unexpected against the backdrop of a global warming trend. Such advances have been attributed to periods of unusually cool summers (Mackintosh *et al.* 2017), positive anomalies in winter precipitation or combinations of the two (Kapnick *et al.* 2014; Forsythe *et al.* 2017).

In southern Norway, the focus of this study, glaciers showed a decade-long period of advance in the 1990s (Nesje *et al.* 1995; Chinn *et al.* 2005; Nesje 2009; Winkler *et al.* 2009; Andreassen & Winsvold 2012; Winsvold *et al.* 2014; Stokes *et al.* 2018), which was attributed to increased winter precipitation. This 'Briksdalsbre Event' (Nesje & Matthews 2012) was particularly prominent in the Jostedalbreen region of western Norway, where 'maritime' glaciers are known to be sensitive predominantly to variations in snowfall and where individual glaciers such as Briksdalsbreen and Fåbergstølsbreen advanced hundreds of metres in little more than a decade (Nesje & Matthews 2012). Away from the coastal mountains, in the more 'continental' Jotunheimen

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region further east, the snowfall anomaly over this period was less significant and glaciers, which appear to be more sensitive to changes in summer temperature (Winkler *et al.* 2010; Nesje & Matthews 2012), did not show such spectacular advances (Winsvold *et al.* 2014).

Interestingly, the LIA responses of glaciers in these two regions are not dissimilar (cf. Bickerton & Matthews 1993; Andreassen 1999; Nussbaumer *et al.* 2011; Imhof *et al.* 2012), which raises questions about the climate factors that were driving the glacier dynamics at that time and also more recently. As for the Briksdalsbre Event, increased precipitation has been invoked to explain the LIA glacier expansion in this part of Norway. Nesje *et al.* (2008a, b) argued that regional summer temperature anomalies in the early 18th century, i.e. in the lead-up to the mid-18th century LIA maximum, were insufficient to account for the full extent of the rapid advance, and that mild humid winters must thus have been the dominant driver. Rasmussen *et al.* (2010) calculated, assuming a LIA temperature anomaly of −0.5 °C to account for the reconstructed geometries of Jotunheimen glaciers, that LIA winter precipitation must have increased by up to 24±22% over several decades. Assuming that the present-day, steeply falling west-to-east precipitation gradient across Norway also existed during the LIA, and that the LIA summer temperature anomaly was indeed as modest as suggested, the implication would be that an even greater increase in snowfall would have been required for glacier expansion at Jostedalsbreen (A. Nesje, pers. comm. 2021).

In this paper, we address the question of the relative importance of summer temperature and winter precipitation in driving the glacier dynamics in the Jotunheimen area since just before the mid-18th-century LIA maximum. Using a nested approach, the *c.* 50-year-long mass balance records for three central Jotunheimen glaciers (Kjøllmoen *et al.* 2019) were correlated with contemporary and early instrumental meteorological data from local and regional weather stations and a summer temperature reconstruction derived from measurements of blue light reflectance of tree ring latewood of Scots pines (*Pinus sylvestris* L.) growing approximately 50 km to the NW of the glaciers. Our use of the tree ring climate proxy in the glacier mass balance reconstructions is based on principles that have been used extensively in other dendro-glaciological studies (cf. Lewis & Smith 2004; Watson & Luckman 2004; Larocque & Smith 2005; Buras *et al.* 2012; Zhang *et al.* 2019). The specific use of blue light reflectance of tree ring latewood builds on and further develops early dendroglaciological work in the same area (Matthews 1977).

The resulting 296-year reconstruction of glacier response to summer temperature was used to test our hypothesis that a relatively small change in summer temperature alone can explain the variance in the Jotunheimen glacier mass balance record over this period. We investigate whether it is necessary to invoke a potentially very large, and arguably unrealistic, increase in winter precipitation to account for specific advance and retreat events of the Jotunheimen glaciers, including the LIA.

## Jotunheimen: physiography and present-day climate

Jotunheimen (61.6°N, 8.3°E; Fig. 1), the highest mountain range in northern Europe, is situated ~150 km inland from the Norwegian west coast. At present, the dominant Atlantic (cyclonic) weather systems pass across southern Norway from west to east, which means that the study area is located in the 'rain shadow' of the coastal mountain range and massifs. The annual precipitation sum for the area may be as low as a quarter of the amount received by the west coast region, including the nearby southern Jostedalsbreen region (Fig. 1; www.senorge.no). The west-to-east precipitation gradient in Norway is thus very steep. For comparison, Bergen, located on the coast ~200 km SW of the study area, receives 2145 mm, while the area around Skjåk (just NW of central Jotunheimen), where the trees for the present study were sampled, is particularly dry with ~300 mm of precipitation per annum (www.met.no).

There is a west-to-east gradient not only in precipitation but also in temperature. In addition to higher overall rainfall, the west coast has relatively cool summers and mild winters. Further inland, in Jotunheimen, climate conditions are distinctly more 'continental' with colder winters, warmer summers and lower precipitation.

## Data and methods

### Overview

Given Jotunheimen's drier climate, we approached the research question by assuming that the present-day variance and trends in the mass balance of Jotunheimen glaciers are predominantly governed by summer melt or ablation, i.e. by summer temperature, and (to a lesser extent) by winter snow accumulation (see Nesje *et al.* 1995: fig. 2B). As the summer budget for glaciers is normally recorded in mid-September (Kjøllmoen *et al.* 2019), we here use the mean temperature over June, July and August ($T_{\mathrm{JJA}}$) as the climate variable driving the summer glacier mass balance $b_{\mathrm{s}}$ and the annual glacier mass balance $b_{\mathrm{a}}$ (cf. Ohmura *et al.* 2007; Farinotti 2013). Coincidentally and conveniently, $T_{\mathrm{JJA}}$ is also routinely identifiable in tree ring studies of north European conifers as the season for summer growth (McCarroll *et al.* 2013; Fuentes *et al.* 2018).

In an attempt to reduce the site-specific response of glaciers in the region, rather than focusing on a single glacier, we considered the mass balance records of three small central Jotunheimen glaciers. The contemporary and early instrumental temperature data used for cali-

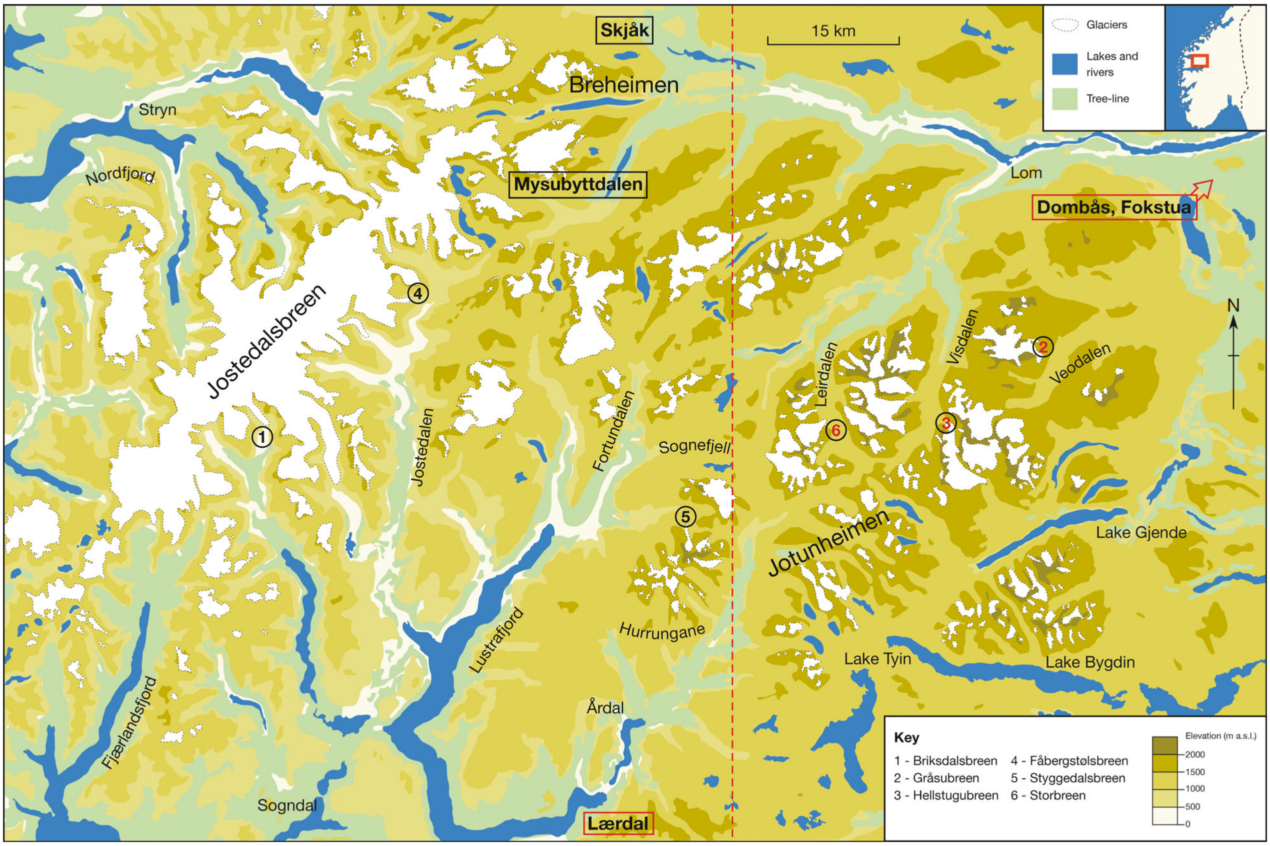

*Fig. 1.* The Jotunheimen region in Norway identifying the location of the three glaciers studied (numbered 2, 3 and 6) as well as selected other glaciers mentioned in the text. Also indicated are the location where the trees were sampled in this study (black boxes, top centre) and the nearest meteorological stations used: Lærdal is on the map (bottom centre) and Dombås and Fokstua are just to the NE of the displayed area. The dashed, red vertical line delineates the grid for the CRU data set used in the nested calibration (the area to the east of the line, which includes the glaciers, is covered by the gridded data).

bration come from four weather stations, some of which are relatively close to the glacier sites and have records going back *c.* 150 years and others are further away but have significantly longer records (*c.* 300 years) (see below). We also use CRU (Climatic Research Unit – University of East Anglia) gridded data (mean summer temperature and winter precipitation sum) for the central Jotunheimen region. The sixth and final summer temperature record used in this study is a proxy record based on the blue light reflectance of tree ring latewood of Scots pines growing at nearby sites (blue intensity; see below). This (minimum) blue intensity parameter has been successfully used in dendroclimatological studies as a cost-effective, sensitive and reliable alternative to maximum latewood density (see Campbell *et al.* 2007; Rydval *et al.* 2017; Björklund *et al.* 2019). Further details on the specific data sets are provided below.

We used a nested approach to correlate the *c.* 50-year-long mass balance records for the Jotunheimen glaciers with the six sets of climate data. This approach aims to maintain stability in the reconstruction as data sets enter and leave the ensemble. We first scaled the six nests of temperature data to the measured annual mass balance record, enabling us to 'convert' summer temperature units to annual mass balance units (m w.e. = metre water equivalent). Using each nest, we then reconstructed the annual glacier mass balance records for the period predating the instrumental record, as far back as the component meteorological and proxy data for each nest allowed. Extending and reconstructing the mass balance record in this way, we were able to investigate the glacier behaviour in response to climate.

## *Synthetic glacier mass balance records*

Three relatively small central Jotunheimen glaciers, Storbreen, Hellstugubreen and Gråsubreen (Fig. 1), whose mass balance has been recorded by the Norwegian Water Resources and Energy Directorate (NVE) since at least 1962 (Kjøllmoen *et al.* 2019), were selected for this study because they are topographically similar in terms of their aspects, surface areas and altitudinal ranges (Østrem *et al.* 1988). Storbreen is the largest of the three (<5 km²), ranges in altitude from 1400 to 2100 m a.s.l., and is best described as a composite cirque glacier (Liestøl 1967). Hellstugubreen is a short valley glacier measuring <3 $\text{km}^2$, and has an altitudinal range of 1480–2230 m a.s.l. (Kjøllmoen *et al.* 2019). Gråsubreen is the easternmost, smallest (<2 $\text{km}^2$) and highest (1830–2280 m a.s.l.) of the three glaciers. Its relatively small mass balance is spatially variable owing to snowdrift, which in some parts can lead to the formation of superimposed ice (Andreassen *et al.* 2015).

The three glaciers show remarkable similarities in their dynamics and share many characteristics with nearly all central Jotunheimen glaciers (Kjøllmoen *et al.* 2019; Table 1, Fig. 2). Still, for consistency and to filter out any site-specific differences in glacier response related to, for example, topographical factors, we compiled, standardized and averaged the three records into one 'synthetic' annual mass balance record. The 'synthetic' glacier may be regarded as representative of the central Jotunheimen region, and it is this record that will be used for the long mass balance reconstruction. This 'average' glacier, referred to as 'Gjennomsnittsbreen' (translating to 'Mean glacier') is thus assumed to record the regional response to climate over time. Specifically, the Gjennomsnittsbreen mass balance record back to 1962 (Fig. 2) captures the typically decreasing trends for annual ($b_a$) and summer ($b_s$) mass balance over the common period 1962–2018, and – critically – also reproduces the trendless individual winter balance records ($b_w$). The record also captures the prevailing negative budget of individual glaciers over the past decades, and the regional lows in single summers (e.g. 2006) or multiyear highs in winter budgets from the late 1980s to the early 1990s.

### *Instrumental climate records*

To enable the mass balance reconstruction back in time beyond the start of the record of NVE measurements, monthly meteorological data were obtained from four weather stations in southern Scandinavia (Fig. 1).

The longest record is provided by Uppsala in Sweden (since 1722); this weather station is also farthest away (>500 km to the ESE of our study area). Trondheim also provides early instrumental data (since 1761) but is closer to the field site (~215 km to the NNE). Despite being relatively far away, both Uppsala and Trondheim share a high degree of variability when compared with the climate of the study region. Comparing individual summer temperature records with Jotunheimen CRU data (version 4.04; see below), the correlation is in the order of 0.8–0.9. Dombås (since 1865) and Lærdal (since 1870) records are shorter in duration but the stations are considerably closer to the glaciers (~55 km to the NE and ~80 km to the SSW, respectively). The fifth climate record used in our nested approach to glacier mass balance reconstruction is derived from mean CRU gridded data (version 4.04; temperature and precipitation; see Harris *et al.* 2020) for four 0.5° tiles (61°62°N; 8°9°E) for the period since 1901. The CRU data are the most local in that the tiles cover the exact locations of the three glaciers under investigation (Figs 1, 3). Critically, no data from any of the aforementioned stations feed into the CRU data so that the five temperature records may be considered independent.

### *Interrogating glacier mass balance in Jotunheimen*

In the context of glacier mass balance studies, winter precipitation and summer temperature are commonly used to characterize the glacier budget in terms of accumulation and ablation, respectively (see e.g. Oerlemans 1992; Oerlemans & Reichert 2000). For the present study specifically, we first tested and established that of all possible appropriate combinations of monthly data (including single months), the 3-monthly means of summer temperature, $T_{\mathrm{JJA}}$ (June, July and August), and 3-monthly totals of winter precipitation, $P_{\mathrm{JFM}}$ (January, February and March), are statistically most significant in explaining the decades-long instrumental measurements of summer balance, $b_s$, and winter balance, $b_w$, for the three selected glaciers (correlation for most weather stations, $R^2 \geq 0.50$, $p < 0.01$). Using the gridded CRU temperature and precipitation data (Harris *et al.* 2020) as well as data from nearby weather stations Lærdal (61.1°N; 7.5°E, ~80 km SSW of the study area) and Fokstua (62.1°N; 9.3°E, ~65 km NE of the study area), a Pearson's correlation analysis found that between 60% and 70% of the individual glaciers' variance in annual mass balance, $b_a$, can be explained by variations in $T_{\mathrm{JJA}}$ whereas only around 15% appears to be controlled by variations of $P_{\mathrm{JFM}}$. All of these correlations are significant at $p < 0.01$. This supports our idea that at least over recent decades the Jotunheimen glacier dynamic response has been mostly driven by summer temperature changes, and that changes in winter precipitation are seemingly less important.

*Table 1.* Inter-series correlation matrices showing Pearson's *r* coefficients for correlations between the mass balance terms (summer balance, $b_s$, winter balance, $b_w$, and annual balance, $b_a$) for the three selected glaciers, and the composite glacier Gjennomsnittsbreen for the period of observation. Correlation coefficients significant at $p < 0.001$.

| Pearson's *r* | $b_s$ | | | $b_w$ | | | $b_a$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | S | H | Gråsu | S | H | Gråsu | S | H | Gråsu |
| Storbreen (S) | | 0.931 | 0.874 | | 0.899 | 0.753 | | 0.891 | 0.759 |
| Hellstugubreen (H) | | | 0.919 | | | 0.848 | | | 0.847 |
| Gjennomsnittsbreen | 0.965 | 0.981 | 0.961 | 0.955 | 0.970 | 0.900 | 0.975 | 0.972 | 0.927 |

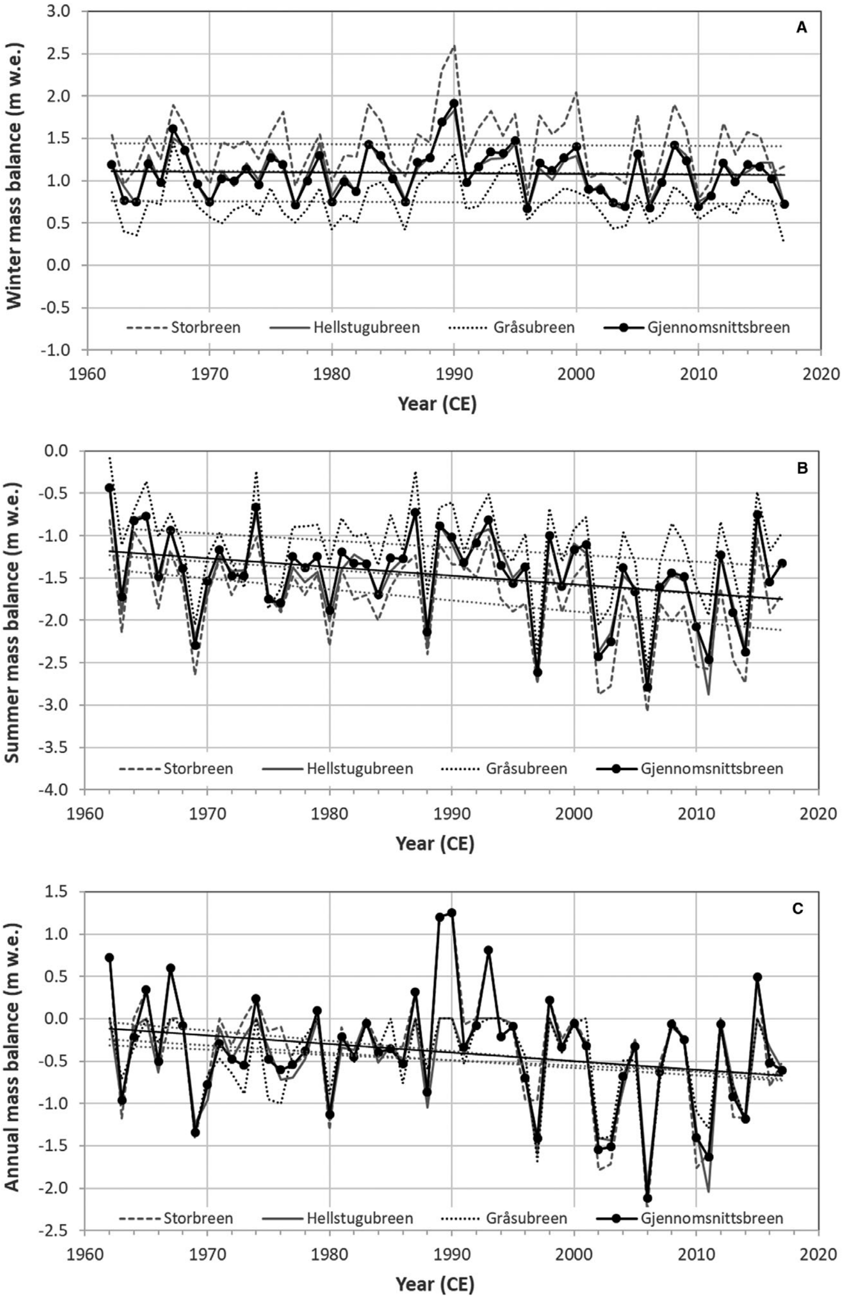

*Fig. 2.* Response of the three Jotunheimen glaciers to: A, winter mass balance; B, summer mass balance ($b_s$); and C, annual mass balance ($b_a$) for the period of direct observation. The common response supports their combination into a single 'synthetic' glacier response (solid lines) for the region (Gjennomsnittsbreen).

### *Tree-ring records: blue intensity as a proxy for summer temperature*

The sixth climate record used here is a proxy record derived from tree rings. We selected 32 tree cores from a larger set that was collected by Blackmore (2006) from living *Pinus sylvestris* L. trees in the Skjåk and Mysubyttdalen area. This area, ~40 km to the NW of the glaciers (Fig. 1), is known to be dry (~300 mm of annual precipitation), and the trees grow near to their altitudinal limit (see Blackmore 2006). We selected cores for blue intensity measurements based upon site location, tree age and the sensitivity of ring widths to climate (Blackmore 2006).

The preparation of the tree samples was very similar to that described by Rydval *et al.* (2014), although our method differs slightly: the cores were treated for 48 h in hot ethanol using a Soxhlet apparatus and then washed repeatedly with boiling deionized water to remove any remaining solvent and water-soluble extractives. Subsequently they were air-dried and then surfaced using progressively finer grades of

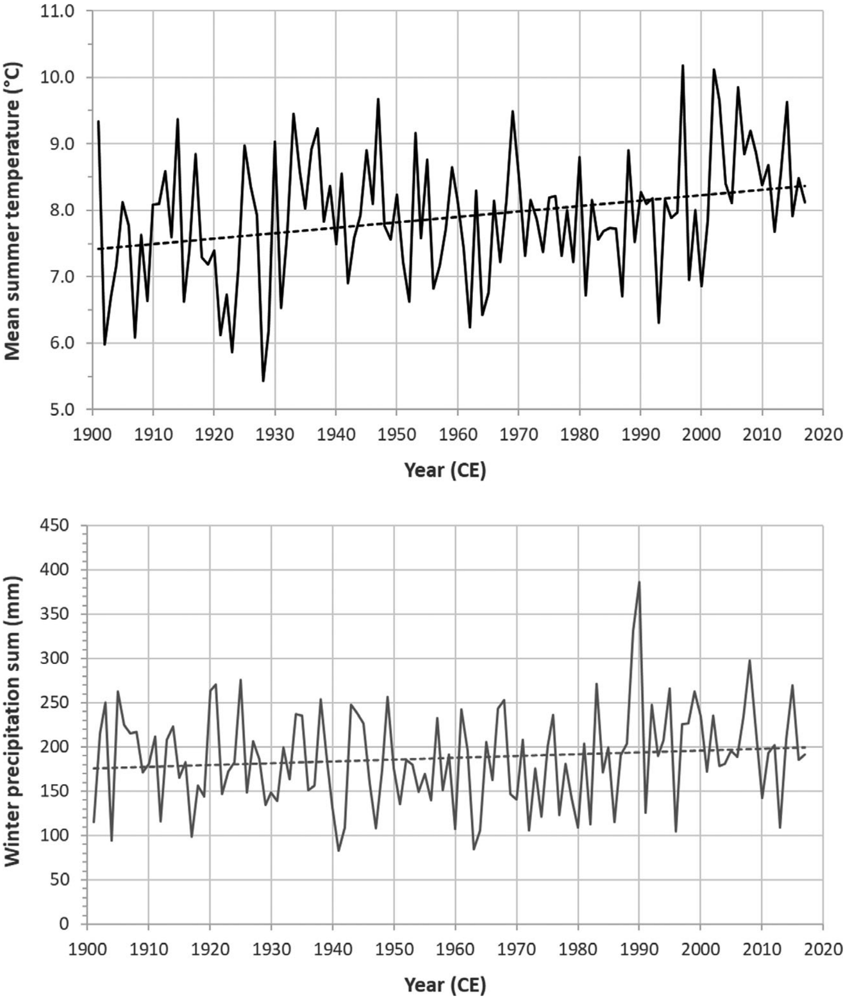

*Fig. 3.* CRU gridded mean summer temperature ($T_{\mathrm{JJA}}$) and winter precipitation total ($P_{\mathrm{JFM}}$) for the study region 1901–2017.

abrasive paper until the wood surface was smooth and the ring boundaries clearly distinguishable. Each surfaced core was then scanned using a calibrated standard flatbed scanner (800 dpi). Measurement of blue reflectance was conducted using Coo Recorder (cybis.se; cf. Rydval *et al.* 2014). Of the original 32 cores, 11 were rejected for various reasons (e.g. narrow ring sequences, breaks, decay/discolouration or transverse twisting). The remaining 21 tree samples from across the two locations were finally used to develop the dendroclimatology reconstruction. Age-related trends were removed using a standard smoothing spline in R package dplR where *n* was fixed as two-thirds of the length of the series (Bunn 2008).

The blue intensity data for 21 cores exhibit a strong inter-tree correlation (rbar = 0.48, 2002–1740). The Expressed Population Signal (Wigley *et al.* 1984) exceeds the commonly adopted indicator value of 0.85 (Speer 2010) for much of the record, but drops to 0.83 at 1740, prior to which it decreases further to 0.80 as replication further declines. Given the high degree of common forcing expressed in the 'blue intensity' data, we conservatively developed the reconstruction from 2002, i.e. the year of sampling, to 1740.

Calibration of the tree ring blue intensity indices with the nearby Fokstua climatic data (since 1923; 62.1°N; 9.3°E, ~60 km ENE of the sample area) was conducted using standard calibration and verification statistics (NRC 2006; McCarroll *et al.* 2015). The blue intensity data exhibit a particularly strong correlation with $T_{\mathrm{JJA}}$ ($R^2 = 0.56$; $p < 0.01$), enabling variance scaling to express the blue intensity index as our sixth record of mean summer temperature, and thus we use it as a proxy for $T_{\mathrm{JJA}}$ (NB: Fokstua was not used otherwise in our reconstruction).

### *The nested approach: correlations and glacier mass balance reconstruction*

To account for the different lengths of the six individual series when reconstructing mass balance for the average central Jotunheimen glacier 'Gjennomsnittsbreen' back in time, we employed a nested approach to reconstruct annual glacier mass balance, $b_a$. Six nests were constructed by calculating mean summer temperatures, $T_{JJA}$ (expressed as deviations from the 1961–1990 climate normal), from the constituent data over the periods covered by these data.

We chose this nesting approach using averaged summer temperature series as single predictors rather than multiple regression in order to avoid the potential effects of multicollinearity, which may lead to overfitted models owing to high correlation between individual series. The number of constituent data sets in our approach logically dropped from six in nest 6 (covering most recent times and coincidentally the most local weather stations) to one in nest 1 (covering the earliest part of the period). The nested approach also allowed us to calculate the skill of our reconstruction of annual glacier mass balance, $b_a$, and the associated uncertainties, as the number of temperature records fell and the distance from the study area increased.

## Results

All of the summer temperature series used, including the tree ring proxy, show – as would be expected – negative relationships with the annual mass balance record, significant at $p < 0.01$ (Pearson's $r$).

As instrumental (observational) glacier mass balance data were available for 1962–2017, we were able to test the stability of the model using the six nests by calculating common calibration and verification statistics ($R^2$, reduction of error, RE, and coefficient of efficiency, CE) for the split periods 2017–1990 and 1989–1962, as well as for the entire period ($R^2$ and SE; Table 2; cf. NRC 2006).

The coefficients of variance ($R^2$) calculated over the full calibration period 1962–2017 for the six nests range between 0.45 and 0.63 (Table 2). In this study, RE remains positive throughout for all nests, for both split periods. The coefficient of efficiency 'fails' (i.e. CE < 0) for the earliest two nests, which possibly reflects the distance of the study site from Uppsala and possible effects of increased precipitation recorded in the early 1990s (see Discussion). We acknowledge that the model performs less well (pass RE, fail CE) for the verification of nests 1 and 2 (used to reconstruct the earliest part of the record) and accept that the confidence in the glacier mass balance reconstructions for the earliest 38 years is therefore lower. The overall verification statistics (for both split periods and the whole interval) improve slightly when the more distal Uppsala record and the blue intensity proxy record that form the constituents of the first two nests are removed (see Table 2; values in brackets). However, this shortened record, using four nests rather than six, does not cover the LIA maximum, which is an objective of this study. Omission of the more distal Uppsala and potentially more 'noisy' blue intensity data in the most recent nests results in a

*Table 2*. Calibration and verification statistics for the six data 'nests' and glacier mass balance for the Jotunheimen region (Gjennomsnittsbreen). Figures in brackets represent the recalculated calibration and verification statistics omitting the blue intensity and Uppsala records (i.e. nests 2 and 1, which fail CE for the second 1989–1962 verification period). Omission of these data and recalculation of the nests result in a more stable reconstruction (improved CE), but a slight reduction in the variance explained for earlier nests. The reconstruction presented covers the period of all six nests but fails CE for the 38 years prior to 1761 (nests 2 and 1 – shaded area in Figs 4 and 5).

| Data | 2017–1990 | | | 1989–1962 | | | 2017–1962 | | | Constituents |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coefficient of variance ($R^2$) | Reduction of error (RE) | Coefficient of efficiency (CE) | Coefficient of variance ($R^2$) | Reduction of error (RE) | Coefficient of efficiency (CE) | Period covered by nest in reconstruction | Coefficient of variance ($R^2$) | Standard error (SE) | |
| Nest 6 | 0.65 (0.59) | 0.65 (0.62) | 0.60 (0.58) | 0.60 (0.66) | 0.57 (0.68) | 0.47 (0.61) | 1961–1901 | 0.63 (0.63) | 0.42 (0.42) | Uppsala, blue intensity, Trondheim, Dombås, Lærdal, CRU |
| Nest 5 | 0.66 (0.60) | 0.66 (0.63) | 0.62 (0.59) | 0.59 (0.65) | 0.55 (0.68) | 0.44 (0.61) | 1900–1870 | 0.63 (0.63) | 0.42 (0.42) | Uppsala, blue intensity, Trondheim, Dombås, Lærdal |
| Nest 4 | 0.65 (0.56) | 0.64 (0.60) | 0.60 (0.54) | 0.52 (0.59) | 0.45 (0.62) | 0.32 0.54) | 1869–1865 | 0.60 (0.58) | 0.43 (0.44) | Uppsala, blue intensity, Trondheim, Dombås |
| Nest 3 | 0.66 (0.44) | 0.61 (0.48) | 0.56 (0.41) | 0.43 (0.38) | 0.23 (0.39) | 0.05 (0.25) | 1864–1761 | 0.55 (0.43) | 0.46 (0.52) | Uppsala, blue intensity, Trondheim |
| Nest 2 | 0.70 (N/A) | 0.63 (N/A) | 0.58 (N/A) | 0.32 (N/A) | 0.07 (N/A) | -0.15 (N/A) | 1760–1740 | 0.53 (N/A) | 0.47 (N/A) | Uppsala, blue intensity |
| Nest 1 | 0.59 (N/A) | 0.54 (N/A) | 0.48 (N/A) | 0.25 (N/A) | 0.09 (N/A) | -0.12 (N/A) | 1739–1722 | 0.45 (N/A) | 0.51 (N/A) | Uppsala |

reduction in the amount of variance explained for each nest (Table 2).

The mean and variance of the climate series listed in Table 2 were then scaled to annual glacier mass balance over the common instrumental period 1962–2017, to 'convert' the normalized summer temperature data $T_{JJA}$ to normalized units of $b_a$. The results of this reconstruction for Gjennomsnittsbreen are displayed in Fig. 4. The errors (SE) are calculated from the regression analysis for each nest, for the appropriate time period, and represent the 95% confidence interval.

This composite $b_a$ record was then used to calculate the cumulative annual glacier mass balance, with the year 2017 being assigned zero with annual net $b_a$ then added sequentially back through time to 1722. The resultant cumulative annual mass balance reconstruction for Gjennomsnittbreen is displayed as the grey line in Fig. 5. For comparison, we have included, in orange, the calculated instrumental cumulative record for Gjennomsnittsbreen over the period 1962–2017. A third reconstruction, based exclusively on combined CRU gridded temperature and precipitation data ($T_{JJA}$ and $P_{JFM}$; see also Fig. 3) back to 1901, is also included as the blue line and demonstrates the combined effect of temperature and precipitation. The red line is a reconstruction based on CRU temperature data alone.

The squared correlation coefficient between the (non-cumulated) reconstruction based upon the combined CRU temperature and precipitation data and the reconstruction based on CRU temperature data alone is very high ($R^2 = 0.8$). Both reconstructions are displayed in Fig. 6; a 5-year running mean filter was used for smoothing.

Using the CRU gridded $T_{JJA}$ and $P_{JFM}$ data we were also able to define the range of combinations of winter precipitation and summer temperature that produce positive and negative variations in annual mass balance (Fig. 7). The points represent every combination of winter precipitation and summer temperature (as deviations from the 1961–1990 mean) since 1901. Assuming again that the selected climate parameters explain most, if not all, variance, all points (i.e. years) plotting left of the line represent positive $b_a$ sums and all points to the right represent a negative $b_a$. It is clear that the majority (~68%) of years since the turn of the last century experienced climatic conditions that were likely to cause a negative glacier mass balance in central Jotunheimen.

## Discussion

Over the period for which mass balance data are available for the three central Jotunheimen glaciers synthesized into Gjennomsnittsbreen (1962–2017), summer temperate $T_{JJA}$ explains 63% of the variability in $b_a$ and winter precipitation $P_{JFM}$ explains only 17%. While we were able to explain around 80% of $b_a$ using $T_{JJA}$ and $P_{JFM}$, this leaves a further 20% unexplained. Part of this may be due to the lower spatial coherence of precipitation compared with temperature. Other factors that contribute are early or late snowfall (before January or after March) and early or late melt (before June or after August). Still, it is clear from our statistical analysis that summer temperatures are the key controlling factor of annual mass balance fluctuations in this region.

Our reconstruction of $b_a$ based solely upon $T_{JJA}$ has a strong and significant relationship for all six nests. Calibration and verification statistics are also positive for all but the two earliest nests – despite maintaining high correlation coefficients – perhaps reflecting the relative

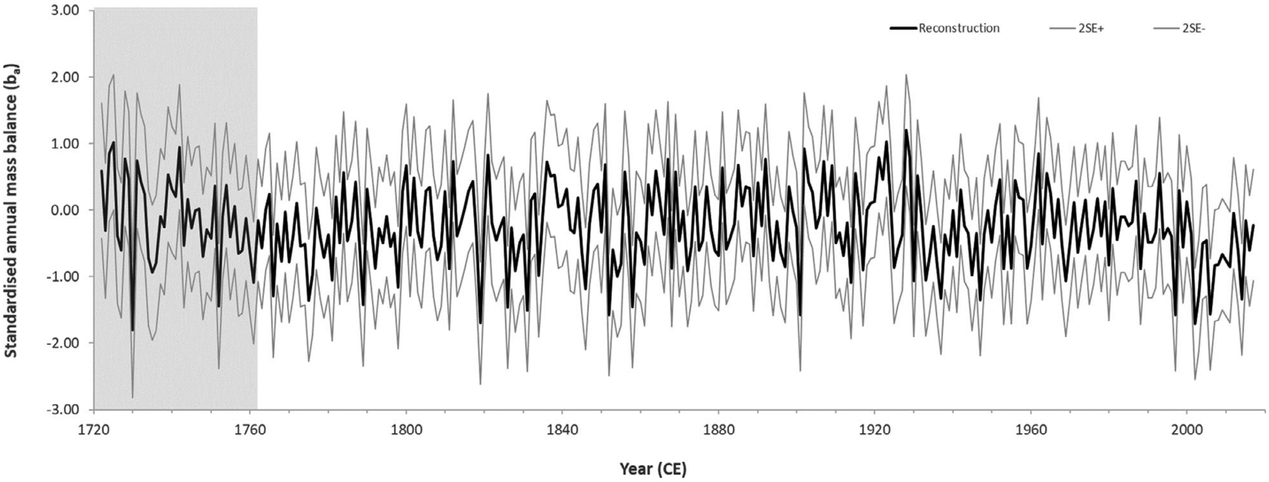

*Fig. 4.* Normalized reconstruction of annual mass balance $b_a$ for synthetic glacier Gjennomsnittsbreen. Grey lines represent the 95% confidence interval, calculated from the regression analysis for each nest and time period (see also Table 2). The shaded area denotes the period covered by nests 1 and 2 for which confidence in the reconstruction is lower (see Table 2).

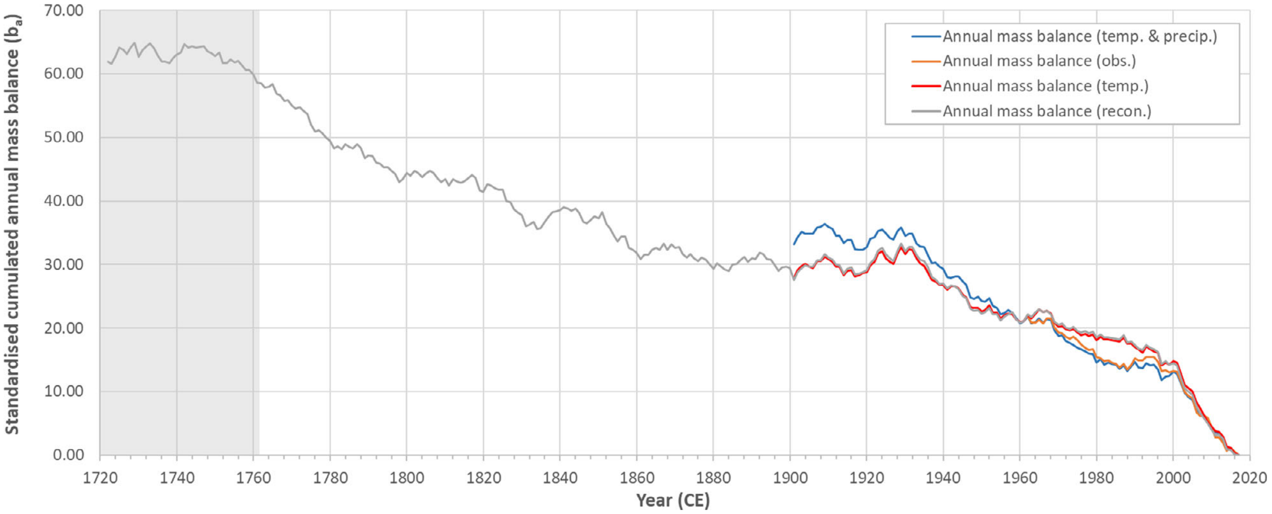

*Fig. 5.* Annual cumulated mass balance ($b_a$) for Jotunheimen region during 1722–2017 (grey line). The year 2017 is assigned zero with annual net $b_a$ then 'added' sequentially back through time. Measured (observed) mass balance record is displayed in orange. Reconstructions based exclusively on CRU gridded data in blue (temperature and precipitation) and red (temperature only). See also Fig. 6. The shaded area denotes the period covered by nests 1 and 2 for which confidence in the reconstruction is low (see Table 2).

quality of the proxy data and more distal and early instrumental data. We emphasize once more that low CE statistics for nests 1 and 2 reduce confidence in the reconstruction for the period before 1761. Any inferences about this early period, highlighted by the shaded areas in Figs 4 and 5, should therefore be considered with the necessary caution.

This strong relationship between $T_{JJA}$ and $b_a$ is also expressed clearly in the cumulative glacier mass balance (Fig. 5), which to a large extent reflects known historical advances and retreats in the glaciers studied. While the glacier snout position of individual glaciers is affected by many factors, such as topography, Fig. 5 gives an impression of the advance/retreat history of our idealized and 'average' Jotunheimen glacier for the period 1722–2017.

The reconstruction of $b_a$ based on only CRU summer temperature (red) performs extremely well against measured annual balance (orange; $R^2$=0.63, 1962–2017) and also strongly matches the reconstruction based upon temperature and precipitation ($R^2$=0.80, 1901–2017; blue line in Fig. 5). This indicates that, although in general terms glacier mass balance is obviously governed by both (winter) precipitation and (summer) temperature, and combining these climate parameters logically produces the best possible results, the loss of explanatory

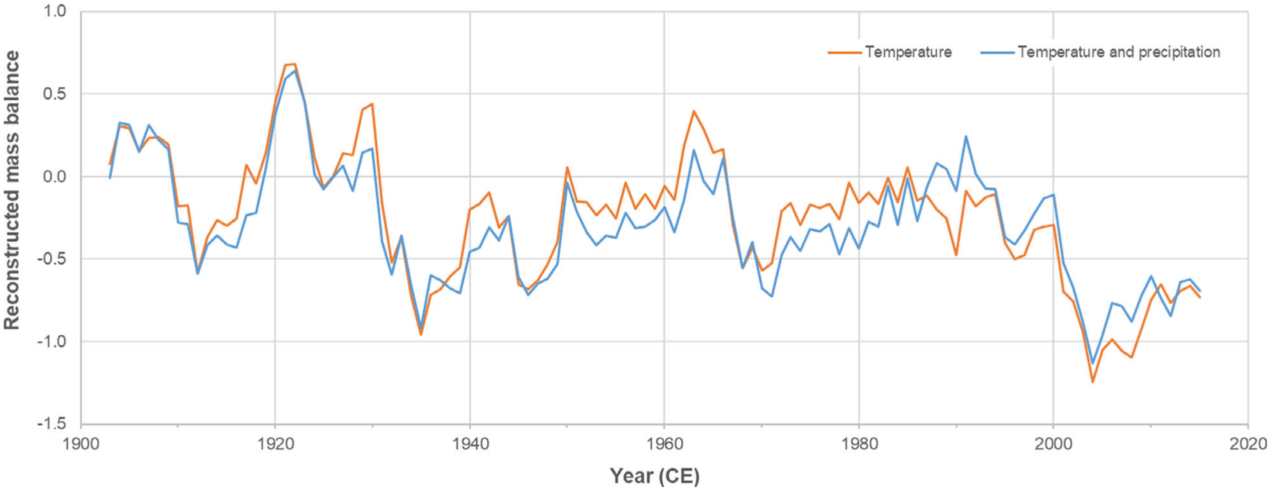

*Fig. 6.* Comparison of the annual mass balance reconstructions ($b_a$) for Gjennomsnittsbreen during 1901–2017 (non-cumulated): the orange line is based on summer temperature only; the blue line is based on a combination of summer temperature and winter precipitation. The reconstructions (smoothed through a 5-year running mean) are based exclusively on CRU gridded data ($T_{JJA}$ and $P_{JFM}$; see also Fig. 3).

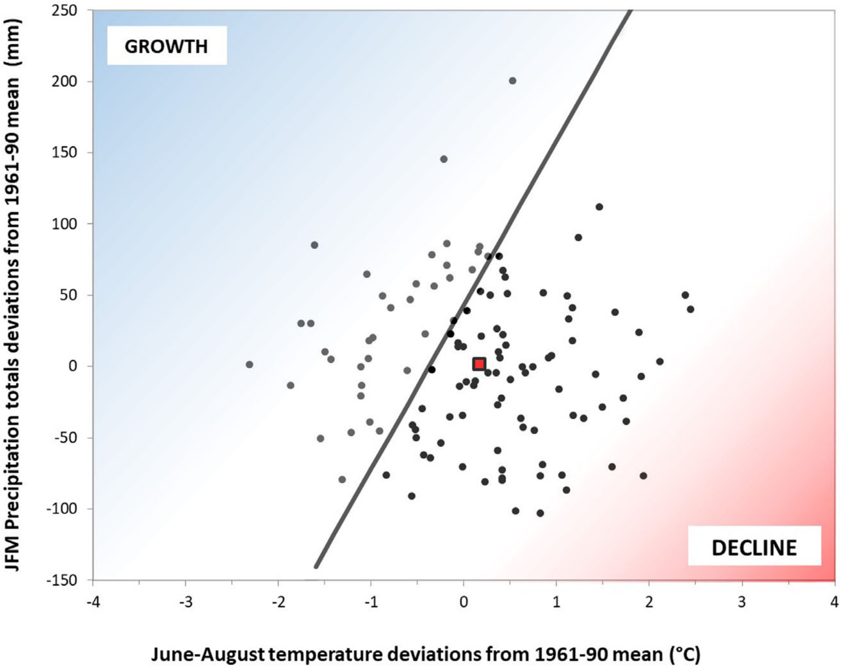

*Fig. 7.* The combination of winter precipitation and summer temperature (as deviations from the 1961–1990 mean) since 1901. The figure assumes that the selected climate parameters explain most, if not all, variance in $b_a$. The black line shows the calculated zero $b_a$ for all combinations of $P_{JFM}$ and $T_{JJA}$ while the red square represents the average $P_{JFM}$ and $T_{JJA}$ conditions since 1901. All points (i.e. years) plotting left of the line represent positive $b_a$, while all points to the right of the line signify a negative $b_a$. The majority (~68%) of years since the turn of the last century experienced climatic conditions that were likely to cause a negative glacier mass balance in central Jotunheimen.

power when using summer temperature alone is, importantly, relatively small for Jotunheimen. However, it is clear from Fig. 5 that the different cumulative balance reconstructions diverge in places with the reconstruction based on both summer temperature and winter precipitation CRU data (blue line) seemingly matching measured annual balance (orange line in Fig. 5) most effectively for the most recent decades. The reason for some of the divergence is clear from Fig. 6, which compares a reconstruction using CRU data for temperature alone and combined temperature and precipitation. During the period of wet winters and warmer summers beginning with the very wet winters of 1989 and 1990 and ending in 2008, the temperature-based reconstruction (grey line in Fig. 5) generally overestimates glacier mass loss, while prior to 1989, when winters were dryer and summers cooler, the temperature-based reconstruction slightly underestimates the measured ice loss.

The reconstructions in Fig. 5 are similar and close around 1960 and immediately prior to this date. Going further back in time, the reconstruction based upon CRU temperature and precipitation data and the 'nested' reconstruction based on temperature alone deviate again, leading to a difference of ~5.4 m w.e. by 1901, when the CRU data end. As there are no actual mass balance measurements for this period, it is difficult to assess the performance of these reconstructions, although it does seem likely that the temperature-based reconstruction slightly and consistently underestimates glacier retreat. Having said that, this deviation still falls comfortably within our annual error estimates (Fig. 4). Prior to 1900 it is hard to speculate about whether this deviation would further increase, although a return to more normal, slightly wetter winters would bring our temperature reconstruction closer to a more complete model. We note here that reconstructing cumulative glacier mass balance is an extremely exacting test, as any small over- or under-estimates will accumulate, and may not always even out for certain time intervals. In this respect, we consider our cumulative reconstruction based upon temperature (the grey line) to be surprisingly good and the one based upon CRU temperature and precipitation (the blue line) to be more reliable (Fig. 5).

There are two very wet winters in the local climate record: 1989, with $P_{JFM} = 331$ mm, and 1990, with $P_{JFM} = 386$ mm, which is approximately double the average winter precipitation over the entire period ($P_{JFM} = 189$ mm). This 2-year period of increased winter precipitation is likely to be the Jotunheimen equivalent of the Briksdalsbre Event (Nesje & Matthews 2012), a well-known period of glacier advance and subsequent retreat in western Norway. In the Jostedalsbreen region, where this Briksdalsbre Event was established and identified, individual glaciers started to advance at annual rates of ~50 m in the early 1990s in response to positive mass balance years in the late 1980s, and continued to do so into the 1990s. The retreat to pre-advance positions for Josteldalsbreen glaciers such as Briksdalsbreen (see Fig. 1) was completed in the early part of the 2000s. The perturbation or cycle was attributed by Nesje & Matthews (2012) to mainly increased winter precipitation during positive NAO (North Atlantic Oscillation) years. The total advance and retreat measured in that region were on the order of hundreds of metres, and it is clear from our data that the effects in Jotunheimen are significantly less. This is perhaps unsurprising given the aforementioned extreme precipitation gradient in Norway. Average winter (January, February and March) coastal precipitation measured at Bergen was 495 mm over the climate normal period 1961–1990: at Fokstua average winter precipitation for the same period was only 80 mm (around 6 times lower). For the three selected glaciers in this study (as well as Gjennomsnittsbreen) the effect of these wet winters is probably best described as a period of reduced retreat rate or relative stillstand, although for individual years (e.g. 1989) an advance of 10 m has been recorded for Storbreen (Kjøllmoen *et al.* 2019). This slowing down of retreat is also reflected in the cumulative measured mass balance curve (Figs 5, 6), which shows a decade-long plateau rather than a distinctive incline. In other words, while it appears that increased winter snowfall drove substantial glacier front positions in Jostedalsbreen, the effect of winter precipitation anomalies in the late 1980s and early 1990s in Jotunheimen seems to have been much less pronounced (see also Fig. 2).

As regional records of precipitation prior to 1900 are rare and in the knowledge that proxy evidence for past changes in winter precipitation is not currently available, it was necessary to compromise and accept the slightly reduced fit of a summer temperature-based model to achieve a longer glacier mass balance perspective.

Extending the nested temperature-based model back through time, a steady decline in glacier mass balance is evident from the time of the LIA maximum (*c.* 1750) to the present day (Fig. 5). This implies that the retreat of the Jotunheimen glaciers has been a persistent feature for nearly 270 years. However, it is also noted that the rate of retreat has not been constant. The period between 1930 and 1962, as well as the period immediately after the LIA maximum, is characterized by a rapid decline, while the annual mass balance shows a plateau in the 1990s, as discussed above. Between 1860 and 1930 the overall rate of decline is relatively slow, while the post-2000 rate of retreat is unprecedentedly rapid in the record, not even matched by the fast retreat reported between 1930 and 1962.

Furthermore, the long-term trend of overall retreat is punctuated by relatively short-lived periods of neutral or occasionally positive glacier mass balance, signifying small glacier advances or periods of stillstand, among which the 1990s 'event' is the most recent. We hypothesize that such periods, characterized in the cumulative mass balance graph by plateaus or positive gradients, may be expressed in the geomorphological record by distinctive terminal (LIA) or recessional moraines. If correct, we should be able to provide some validation for such moraine-building events in our temperature-based reconstruction with an independent record of such events based on lichenometry-dated clusters of moraines at different glacier forelands in Jotunheimen. This independent record is provided by Matthews (2005), who developed a post-LIA chronology and identified a total of 12 regional moraine-building events (Table 3; cf. Bickerton & Matthews 1993). To qualify as a regional moraine-building event, Matthews (2005) required ridges to have formed at five or more Jotunheimen glaciers of the 16 studied. This strict requirement meant, for example, that none of the short moraine sequences formed in the 1980s to 2000s (i.e. including the 'Briksdalsbre Event') at Storbreen and Styggedalsbreen (Fig. 1; see Hiemstra *et al.* 2015) are sufficiently widespread to feature in the list.

In all, 10 out of the 12 events are identifiable from the retreating trend in our Jotunheimen summer temperature-based glacier mass balance reconstruction (Table 3, Fig. 5). Comparison of the timing of these with the record of dated moraines even shows a close coherence with 11 of the 12 events falling within the dating range of the moraines across the region (including event 2, Table 3). Start and end dates may differ slightly between the lichenometry-based dated record and our temperature-based model, and some events are more pronounced than others, but this very high agreement (10 of 12 events) would further support our thesis of summer temperature ($T_{\mathrm{JJA}}$) as the principal driver for glacier response in Jotunheimen, at least since the 1740s.

From Fig. 7, which uses measured temperature and precipitation to define the winter precipitation and summer temperature required for positive and negative annual glacier mass balance, it is possible to estimate the

*Table 3.* Moraine-building events with each 'cluster' represented at five or more Jotunheimen glaciers (Matthews 2005). The earliest moraine cluster is consistent with a traditional mid-18th century date for the regional Little Ice Age glacier maximum in Jotunheimen.

| Regional moraine-building event | Period | Matched in reconstruction? |
|---|---|---|
| 1 | 1743–1750 | Yes (1738–1748) |
| 2 | 1762–1771 | No (but positive $b_a$ 1762–1763) |
| 3 | 1782–1790 | Yes (1781–1788) |
| 4 | 1796–1802 | Yes (1798–1803) |
| 5 | 1811–1818 | Yes (1811–1818) |
| 6 | 1833–1838 | Yes (1835–1842) |
| 7 | 1845–1854 | Yes (1847–1851) |
| 8 | 1860–1868 | Yes (1861–1868) |
| 9 | 1871–1879 | No |
| 10 | 1886–1898 | Yes (1884–1892) |
| 11 | 1915–1922 | Yes (1917–1925) |
| 12 | 1927–1934 | Yes (1917–1932) |

changes in climate required for glacier growth and retreat. Clearly, changes in both winter precipitation and summer temperature or some combination of the two will lead to changes in $b_a$. However, if we look at the instrumental data for the region (Fig. 3), there is little long-term change in precipitation. Summer temperature, on the other hand, has clearly winter increased (Fig. 3). A large body of published research has concluded that annual temperatures during the LIA were cooler than those of the past *c.* 100 years, which includes research on summer, winter and annual temperatures (Matthews & Briffa 2005 and references therein). Much of this research has been carried out, across Fennoscandia, using tree ring-based proxies, which will clearly be biased towards the summer growing season (e.g. Briffa *et al.* 1992; Svarva *et al.* 2018; Björklund *et al.* 2020). Reconstructions of past precipitation are more difficult, especially winter precipitation, and in Fennoscandia are mostly based on glacier data and the hypothesis that LIA advances were driven mainly by winter precipitation (e.g. Nesje & Dahl 2003; Rasmussen *et al.* 2010).

Our data provide grounds to challenge this hypothesis, and therefore the basis for using winter precipitation in regional glacier mass balance reconstructions. Figure 7 shows that if winter precipitation is held constant at the average level since 1901 (red square in Fig. 7), a reduction in summer temperatures of ~0.5 °C from the mean since 1901 is all that is required to reverse glacier decline. However, it may be possible, if a simple colder, drier winter scenario is followed, for a slightly reduced summer temperature to be required to achieve the same net result. Assuming that long-term winter precipitation was 50 mm lower in the past *c.* 120 years, for example, a reduction of ~1 °C in summer temperature would be required to increase $b_a$.

Conversely, if summer temperature is held constant at the average since 1901 (red square in Fig. 7), an increase in winter precipitation ($P_{JFM}$) of >62 mm is required to halt glacier decline. This level of winter precipitation is not impossible but has only occurred 15 times since 1901, including in the aforementioned very wet 'Briksdalsbre winters' of 1989 and 1990. Maintenance of this level of winter precipitation over a period of decades – as would be assumed to be necessary to account for the recorded LIA glacier advance in Jotunheimen – seems unlikely, especially if winter temperatures were lower than they are today (cf. Leijonhufvud *et al.* 2008). Clearly, winter precipitation affects glacier mass balance in the region, although this is more difficult to estimate and quantify with available (palaeo) data. Events such as those seen around *c.* 1989/1990 are very likely to have occurred in the past. Occasional wet winters combined with a long-term reduction in summer temperature would lead to even more rapid glacier advance. We therefore do not discount the role of winter precipitation or atmospheric circulation change, but rather demonstrate here that a large, prolonged increase in winter precipitation is not a requisite to invoke large, long-term changes in glacier balance in the Jotunheimen region. While short-term positive changes in mass balance are likely to have been precipitation driven, winter precipitation is likely to have played a secondary role to summer temperature in long-term Jotunheimen glacier dynamics.

## Conclusions

Developing understanding of the long-term changes in the cryosphere is important in the study of past climatic change. This study has combined instrumental and proxy data to develop a reconstruction of past summer temperature that was then used to reconstruct glacier mass balance in the Jotunheimen area of southern Norway since just before the LIA maximum of 1750. The presence of long-lived temperature-sensitive trees in the region and the potential for extracting hydroclimate information from tree ring stable oxygen isotopes (e.g. Loader *et al.* 2020; Büntgen *et al.* 2021) offer potential for extending the reconstruction back through the last millennium.

Our reconstruction of cumulative mass balance identified several short-term glacier advances or periods of stillstand which almost perfectly agree with independent records of lichenometry-dated moraines across the region (Matthews 2005). We find that the glaciers studied in this region appear to have been declining since the mid-18th century. The rate of this decrease has remained relatively constant through the study period.

An aim of this study was to try to establish whether or not the recent glacial history of retreat and advance could be explained adequately by summer temperature, or if a large increase in the amount of winter precipitation would be needed to explain trends in glacier dynamics since the LIA. Our results indicate that a large increase in precipitation is not required to drive the LIA advance observed in this region. However, as is clear from the Briksdalsbre Event (Nesje & Matthews 2012), large increases in winter precipitation will strongly affect glacier growth. We do not ignore the fact that changes in the amount and distribution of precipitation through time are likely to have occurred and to have influenced mass balance in this region. However, we suggest that large precipitation events such as this are likely to have been relatively infrequent across this region. We find no clear evidence for large increases in winter precipitation maintained over a prolonged period. Specifically, we find little evidence to suggest that LIA winters would have been mild and wet.

There is a large body of research literature that suggests that annual and summer temperatures during the LIA period were cool (PAGES 2k Consortium 2013). Our research suggests that variations in summer temperature may be all that is required to drive and to describe the observed long-term regional glacier growth and retreat in Jotunheimen.

It can be concluded from our data that average summer temperatures in Jotunheimen have been too warm since *c.* 1750 for glacier growth in the region, and that recent increases in summer temperature – particularly in the past two decades – have accelerated this retreat. Interestingly however, it needs to be pointed out that much of the negative change in glacier mass balance had already occurred prior to the onset of the Industrial Revolution around 1850. In fact, the climatic conditions of most years since 1750 must have contributed to glacier retreat. We have to assume that the climatic conditions in Jotunheimen prior to 1750, the period usually referred to as the LIA, must have promoted glacier growth for a prolonged time. Using realistic assumptions about winter temperature and snowfall, our simple calculations show that summer temperatures during the LIA were potentially only ~0.5–1 °C cooler than today.

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*Author contributions.* – JFH led the study with the following contributions: sample collection and fieldwork (PRG); laboratory preparation, image and data analysis (NJL, JFH), calibration and statistical analyses (GHFY), preparation of the manuscript (JFH, NJL, GHFY).

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