Widespread and accelerating glacier retreat on the Lyngen Peninsula, northern Norway, since their 'Little Ice Age' maximum

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ABSTRACT: The recession of mountain glaciers worldwide is increasing global sea level and, in many regions, human activities will have to adapt to changes in surface hydrology. Thus, it is important to provide up-to-date analyses of glacier change and the factors modulating their response to climate warming. Here we report changes in the extent of >120 glaciers on the Lyngen Peninsula, northern Norway, where glacier runoff is utilised for hydropower and where glacial lake outburst floods have occurred. Glaciers covered at least 114 km^2 in 1955 and we compare this inventory with those from 1988, 2001, and a new one from 2014, and previously-dated Little Ice Age (LIA) limits. Results show a steady reduction in area (~0.3% a^{-1}) between their LIA maximum (ca. 1915) and 1988, consistent with increasing summer air temperatures,

but recession paused between 1988 and 2001, coinciding with increased winter precipitation. Air temperatures increased 0.5 °C per decade from the 1990s and the rate of recession accelerated to ~1% a^{-1} between 2001 and 2014, when glacier area totalled ~95.7 km^2. Small glaciers (<0.05 km^2) with low maximum elevations (<1400 m) experienced the largest percentage losses and, if warming continues, several glaciers may disappear within the next two decades.

1. INTRODUCTION

Despite concerns over the acceleration in mass loss from ice sheets in Greenland and West Antarctica (Shepherd and others, 2012), the shrinkage of smaller mountain glaciers and ice caps was broadly equivalent to the combined loss from both ice sheets between 2003 and 2009, and accounted for 29 ± 13% of observed sea level rise (Gardner and others, 2013). It is important, therefore, to provide up-to-date assessments of how mountain glaciers and ice caps from different regions are changing in response to climate change, both to refine future projections of sea level rise (e.g. Huss and Hock, 2015) and to better understand the factors that modulate glacier retreat (e.g. Whalley and others, 1989; De Beer and Sharp, 2009; Paul and Andreassen, 2009). Changes in mountain glaciers also have important implications for surface hydrology, most notably in terms of changes in runoff from glacier catchments (e.g. Bliss and others, 2014), and changes in glacial lakes, which pose a serious hazard in some regions (e.g. Carey, 2005).

One country where these issues are particularly acute is Norway (e.g. Liestøl, 1956; Jackson and Ragulina, 2014; Engelhardt and others 2014). Although glaciers only cover 0.7% of the area of the mainland (Andreassen and others, 2012a), 98% of Norway's electricity comes

from hydropower, of which 15% comes from catchments that contain glaciers (Andreassen and others, 2005). Furthermore, despite Norway's long tradition of monitoring glaciers, and the compilation of several glacier inventories (Liestøl, 1962, Østrem and others, 1973; Andreassen and others, 2012a; Winsvold and others, 2014), there remain several regions which have evaded detailed scrutiny and lack an up-to-date assessment of glacier change. One such region is the Lyngen Peninsula in Troms County, northern Norway (Fig. 1). This peninsula hosts >120 glaciers, ranging from small cirque glaciers, to larger valley glaciers and plateau icefields, and which cover an area in excess of 100 km^2 (Østrem and others, 1973; Andreassen and others, 2012a). Runoff from glaciers in this region is an important source of hydro-electricity generation and the area is popular for both winter and summer tourism. There are also several proglacial lakes in the region, and there have been major outburst floods (e.g. Liestøl, 1956; Aitkenhead, 1960; Whalley, 1971), some of which have potential to damage local infrastructure (Jackson and Ragulina, 2014). Previous work, mostly undertaken in the 1970s and 1980s, highlighted the variable response of a small number of glaciers (generally <10) depending on their elevation (Gellatly and others, 1986; Gordon and others, 1987; Whalley and others, 1989; Rea and others, 1999; Andreassen and others, 2000), but there has been no detailed and systematic assessment of recent glacier change across the entire peninsula.

In this paper, we compare area changes from existing glacier inventories from 1955, 1988, 2001 together with a new inventory from 2014. We also examine glacier area and length changes for a sub-sample of glaciers with moraines dated to ca. 1915 and ca. 1750 (Ballantyne, 1990) and compare trends in glacier change with both climatic and topographic data.

2. STUDY AREA AND PREVIOUS WORK

The Lyngen Peninsula, located in maritime northern Norway (Fig. 1), is a deeply incised mountain region composed of predominantly gabbroic bedrock (Randall, 1971). It is characterised by a landscape of selective linear erosion, whereby flat-topped plateau surfaces survive between deeply-incised glacial valleys (Corner, 2005a, b). The peninsula is flanked on either side by two large fjord systems: Ullsfjord to the west and Lyngenfjord to the east (the southern part of Lyngenfjord is known as Storfjord). These hosted major outlet glaciers during deglaciation of the former Fennoscandian Ice Sheet (Stokes and others, 2014), which produced several extensive moraine systems as the ice margin paused or readvanced during overall recession to the inner fjord valleys by ~10 cal. yr BP (Anderson, 1968; 1968; Corner, 1980). Subsequent retreat during the early Holocene was punctuated by minor readvances and still-stands that created impressive suites of moraines in front of some glaciers (Ballantyne, 1990; Bakke and others, 2005). It is thought that many glaciers disappeared at some point between 8,800 and 3,800 cal. yr BP, as a result of higher summer temperatures and/or reduced winter precipitation, before reforming between 6,000 and 2,000 cal. yr BP (Nesje and others, 2008).

The hydrological divide runs approximately north-south along the central spine of the Lyngen peninsula, which supports several plateau icefields. The highest (1,833 m) and largest (10 km^2) plateau icefield is Jiehkkevárri, which feeds several valley glaciers (Rea and others, 1999). At lower elevations, numerous smaller valley and cirque glaciers exist (Gellatly and others, 1986; Gordon and others, 1987), with some extending below 400 m (Andreassen and others, 2012a). Total glacier coverage was estimated at ~140 km^2 in the 1950s (Østrem and others, 1973), or around 10% of the peninsula (Ballantyne, 1990). At elevations >1,600 m, the glaciers and plateau icefields are thought to be cold-based, whereas those at lower elevations are warm-based, with the possible exception of some cold-based frontal margins (Whalley and others, 1981; Gordon and others, 1987; Gordon and others, 1988).

94   Some of the first observations of glaciers in the region were made by tourists and

95   mountaineers in the mid- to late-1800s (e.g. Forbes, 1853; Hastings, 1899; Slingsby, 1898; Le

96   Blond, 1908). Their reports often contained basic information about the glaciers and they were

97   the first to report the rapid drainage of a glacial lake (Strupvatnet) adjacent to Strupbreen in

98   1898 (see Liestøl, 1956). A Durham University expedition witnessed another sudden drainage

99   of Strupvatnet in August 1957 (Aitkenhead, 1960). These early reports included a number of

100   photographs and anecdotal evidence, which subsequent workers utilised to reconstruct glacier

101   changes (e.g. Whalley, 1973; Gellatly and others, 1986; Whalley, 2004; Whalley and

102   Parkinson, 2016).

103   Following Liestøl's (1962) list of the numbers and areas of glaciers in Norway, Østrem

104   and others (1973) compiled the first comprehensive inventory of the Lyngen Peninsula in the

105   publication of the 'Glacier Atlas of Northern Scandinavia'. This inventory was based on maps

106   and aerial photographs from the 1950s and 1960s and included information on each glacier,

107   such as the size (area and length), aspect (of both the accumulation area and ablation area) and

108   elevation (minimum and maximum), together with location maps. However, it was not until

109   the mid-1980s that attempts were made to investigate any changes in the glaciers, and several

110   studies emphasised the importance of topography in controlling their response to climatic

111   warming (Gellatly and others, 1986; Gordon and others, 1987, 1995; Whalley and others, 1989,

112   1995; Andreassen and others, 2000), influenced in part by some of the early work by Gordon

113   Manley (e.g. Manley, 1955). Gellatly and others (1986), for example, photographed a small

114   number of glaciers and icefields in the southern part of the peninsula and compared these to

115   photographs taken on an expedition in 1898 (Le Blond, 1908). They recognised the important

116   connection between the high elevation plateau icefields and lower elevation valley glaciers that

117   they nourish. They found that rapid down-wasting and recession of valley glaciers since the

118   early 1900s was associated with extensive wastage of icefields on the lower plateau summits

119   (~1,400-1,500 m), whereas little change was recorded in the appearance of the high plateau ice

120   caps (~1,600 m) (see also Gordon and others, 1987; Whalley and others, 1989; Rea and others,

121   1999).

122   In terms of their most recent maximum, early anecdotal observations and documentary

123   evidence from local people suggested that glaciers were much more extensive in the mid-18th

124   century (ca. 1750), with some descending close to sea level, such as Strupbreen (Nielsen, 1896;

125   Liestøl, 1956; Andreassen and others, 2000). However, lichenometric measurements in front

126   of 21 glaciers led Ballantyne (1990) to conclude that the majority of glaciers in his study

127   exceeded or nearly exceeded their mid-18th century maxima during a period of advance dated

128   to 1910-1920, and that only a handful of larger glaciers were more extensive in the 1750s, and

129   only by a small distance (tens of metres). Thus, he argued that conditions for glacier growth

130   may have been less favourable in the mid-18th century than around the beginning of the 20th

131   century. He hypothesised that a reduction in winter snowfall during the mid-18th century may

132   have resulted from a more southerly location of the North Atlantic oceanic polar front and that,

133   as a consequence, southern Norway may have received increased snowfall, thereby explaining

134   why the mid-18th century advance was generally much more extensive further south (Grove,

135   2004).

136   There are no mass balance records for any glaciers on Lyngen, with the nearest being

137   around 100 km to the north-east at the Langfjordjøkelen ice cap (Andreassen and others, 2012b;

138   Giesen and others, 2014; see Fig. 1). The Norwegian Water Resources and Energy Directorate

139   (NVE) have mapped individual glaciers or small numbers of glaciers in the region (e.g. NVE,

140   1985; Andreassen and others, 2000; Hausberg and Andreassen, 2009) and compiled length

141   change records for two glaciers since 1998 (Koppangsbreen and Steindalsbreen) and one since

142   2007 (Sydbreen), with retreat rates typically between 10 and 20 m a^{-1} over the last decade or

143   so (Kjøllmoen and others, 2011; Kjøllmoen and others, 2016). In addition to the historical lake

144   outbursts at Strupbreen (Liestøl, 1956; Aitkenhead, 1960), several floods have recently been

145   recorded at Koppangsbreen, most notably in summer 2013 when several properties were

146   evacuated in the village of Koppangen, and prompting the construction of flood defences

147   (Jackson and Ragulina, 2014).

148

149   3. DATASETS AND METHODS

150   *3.1. Previous Glacier Inventory Data (1955, 1988, 2001)*

151   Data from 1955 were compiled by Winsvold and others (2014) who digitised glacier

152   outlines from 1:50,000 topographic maps in the N50 series from the Norwegian Mapping

153   Authority. This inventory (which they referred to as GI_{n50}) includes data for the whole of

154   mainland Norway and from a range of dates between 1947 and 1985, but outlines from the

155   Lyngen Peninsula were extracted from maps produced from 1955 aerial photographs. The 1955

156   maps were scanned and georeferenced and glacier outlines were digitised on-screen (Winsvold

157   and others, 2014), see Fig. 2.

158   The 1988 glacier outlines were also created by Winsvold and others (2014) and formed

159   part of their GI_{1990} inventory for mainland Norway. Data pertaining to the Lyngen Peninsula

160   were obtained from a Landsat 4 Thematic Mapper (TM) image (path 197, row 11) from 25th

161   August 1988. Glacier outlines were derived automatically from a TM3/TM5 ratio image, using

162   a threshold ≥ 2 and with an additional threshold from TM1 (>60) to improve the outlines of

163   glacier areas in heavy shadow (cf. Paul and Kääb, 2005; Andreassen and others, 2008). A

164   median filter (3 by 3 kernel) was applied to reduce noise in areas of shadow and remove isolated

165   pixels outside glacier areas, usually snow patches. Glacier pixels were then converted to a

166   vector (.shapefile) format and a small number of glaciers were edited manually to correct for

167 cases of supraglacial debris cover (very rare on Lyngen), glacier-lake interfaces, clouds, or

168 heavy shadow that hampered the automated techniques (Winsvold and others, 2014).

169   The 2001 data for the Lyngen Peninsula were first published in Hausberg and

170 Andreassen (2009) and were subsequently edited and finalised for incorporation into the

171 Inventory of Norwegian Glaciers (Andreassen and others, 2012a). Glacier outlines were

172 derived from a Landsat 7 Enhanced TM Plus image (path 198, row 11) from 20th August 2001

173 and used the same methods as the 1988 data, but using a threshold ≥ 2.4 on the TM3/TM5 ratio

174 image.

175

176 *3.2. A new glacier inventory for 2014*

177   The 2014 inventory was generated for the purposes of this paper and was compiled only

178 for the Lyngen Peninsula (Fig. 1). To ensure consistency with the previous inventories from

179 1988 and 2001 (in terms of spatial and spectral resolution), we searched the USGS Earth

180 Explorer repository (http://earthexplorer.usgs.gov/) for Landsat 7 and 8 scenes with minimal

181 cloud cover and from close to the end of the ablation season. A Landsat 8 scene (path 197, row

182 11) from 25th August 2014 was deemed most suitable (Fig. 1). The Landsat 8 Operational Land

183 Imager (OLI) and Thermal Infrared Sensor (TIRS) images contain more bands than the Landsat

184 ETM+, but bands 2, 3, 4, 5 and 6, cover similar wavelengths to the Landsat TM and ETM

185 sensors 1, 2, 3, 4 and 5. Thus, we derived glacier outlines from an OLI band 6/4 ratio image.

186 Following Paul and others (2013), we selected a threshold as low as possible before the number

187 of misclassified pixels increased, and found that values greater than 1.3 were best able to

188 capture glaciers areas cast in shadow (Fig. 3a). We gained confidence in our selection of this

189 threshold by cross-checking areas of shadow against both the 2001 inventory and from high

190 resolution aerial photographs available at http://www.norgeibilder.no (Fig. 3c) We also

191 experimented with an additional threshold in the OLI band 2 (equivalent to TM band 1), but

192 were unable to improve on the OLI band 6/4 ratio image, without the number of misclassified

193 pixels increasing. As in the 1988 and 2001 datasets, we then applied a median filter (3 by 3

194 kernel) and converted the binary image to a vector (.shapefile) format. The outlines of very few

195 glaciers were edited manually and mostly to account for glacier-lake interfaces and a small

196 amount of cloud cover that affected the accumulation areas of five small glaciers north of

197 Vestbreen (glacier IDs 231, 232, 234, 236 and 237: all ID numbers refer to the Norwegian

198 Glacier Inventory from Andreassen and others, 2012a) and one north of Steindalsbreen (glacier

199 ID 281). To ensure consistency when comparing individual glacier area changes, we then

200 superimposed the ice divides from the 2001 dataset. It became clear that some glacier polygons

201 from the 2001 dataset had split into two or more separate glacier polygons in the 2014 dataset.

202 In those cases, the separate glacier polygons were aggregated to give a cumulative area for the

203 2014 inventory.

204

205 *3.3. Glacier length and area changes since the 'Little Ice Age'*

206 For a small number of glaciers, we were able to supplement the inventory data described above

207 with historical data of glacier extent based on moraine mapping and dating published in

208 Ballantyne (1990). He mapped up to four nested Neoglacial moraine sequences, labelled M1

209 (youngest) to M4 (oldest), in front of 21 glaciers spread throughout the peninsula. Using

210 lichenometric, dendrochronological and historical evidence, the youngest of these limits (M1)

211 was dated to around 1910-1920, and is often characterised by vegetation trimline, with only

212 very sparse vegetation cover inside the moraine limit (Fig. 3c). The next oldest (M2) moraine

213 limits were very hard to distinguish and were only mapped as fragments in front of 4 glaciers

214 (see Table 1 in Ballantyne, 1990), where they gave ages of 1865-1880 and 1825-1845. M3

215 moraine limits were generally much larger and easily recognisable and coincided with a clear

vegetation trimline characterised by mature stands of trees and shrubs (*Betula pubescens* and *Salix* spp.) outside the moraine ridges, but with only occasional immature individuals inside. They gave ages of ca. 1750 and, as noted above, Ballantyne (1990) found that many glaciers exceeded or nearly exceeded this mid-18th century maximum during the 1910-1920 (M1) advance.

Using high-resolution aerial photographs available at http://www.norgeibilder.no (mostly from 2011 (Fig. 3c), but also 2006), together with Ballantyne's (1990) maps (e.g. his Figs 3 and 4), we were able to confidently identify previously mapped M3 (ca. 1750) and/or M1 (ca. 1910-1930) moraines at 18 glaciers, and incorporate these limits into our GIS to compare with the glacier inventory data (see Section 3.1). However, length changes could only be extracted from 10 glaciers which had an obvious terminus in a valley (some were small plateau ice-fields will no obvious terminus). These tended to be large glaciers (e.g. Fig. 3c) and they include the 4 largest glaciers and 7 out of the top 10 largest glaciers. Several of these glaciers were visited in the field to cross-check our mapping of the moraine limits, including Koppangsbreen, Vestbreen, Midtbreen and Sydbreen in 2015, Steindalsbreen in 2015, 2016 and 2017, and Rottenvikbreen in 2017. In order to map the glacier areas for these moraine limits, we used the 1955 inventory outlines (Section 3.1) and simply extrapolated the down-ice area to fit with the moraine limit (Fig. 3c) (cf. Baumann and others, 2009). This assumes that the glacier was only larger at its lower elevation limits, which is reasonable for most of these larger valley glaciers, but it is important to note that this represents a minimum area at these older limits. To simplify the calculation of rates of change, we used dates of 1750 and 1915 for the M3 and M1 moraines, respectively (Fig. 3c).

3.3. Errors and uncertainties

240   The 1955 data were derived from digitising glacier outlines from 1:50,000 topographic maps

241   in the N50 series from the Norwegian Mapping Authority, which were based on aerial

242   photography. Sensitivity analysis using different investigators to digitise glacier outlines from

243   the same maps revealed a high degree of accuracy (Winsvold and others, 2014), but there is a

244   much larger uncertainty in terms of how glaciers were originally mapped from the aerial

245   photographs, which would have been influenced by the working methods and mapping

246   principles of the cartographers at the time. We compared glacier outlines (vector shapefiles)

247   from 1955 with more recent inventories (e.g. Fig. 2), which indicated that most glaciers appear

248   to have been reasonably portrayed and were larger in the 1950s, which is consistent with a

249   number of other studies on the Lyngen Peninsula (cf. Østrem and others, 1973; Gordon and

250   others, 1987; 1995; Winsvold and others, 2014). However, it is clear that a number of glaciers

251   (n = 22) were not depicted on the original maps and that, for others, their outlines appear to be

252   much smaller than expected in their upper (accumulation) areas (see Fig. 2). In addition, there

253   were some discrepancies between the location of ice divides in the 1955 glacier outlines,

254   compared to more recent inventories, particularly in the vicinity of the plateau-icefields such

255   as Jiehkkevárri. Thus, where there was an obvious error in the delineation of the upper areas

256   of the glaciers and/or their ice divides, these were edited to match the next most recent outlines

257   in 1988, but only in the upper areas of the glacier. Edits were made to 21 of 126 glaciers that

258   were part of the 1955 inventory and none of these glaciers were used in our area and length

259   change measurements since the LIA. Taken together, we conservatively estimate that the total

260   area of the glaciers included in our edited 1955 inventory is ±5%.

261   The band ratio method that was used to produce the 1988, 2001 and new 2014 data is

262   generally viewed as being accurate to between ±2-5% in the absence of large amounts of

263   supraglacial debris (Paul and others, 2013), which is the case for the Lyngen Peninsula.

264   Winsvold and others (2014) quoted an error of ±3% for the 1988 and 2001 inventories, although

265 they may be more accurate than this based on a comparison of glacier outlines from Landsat

266 imagery and aerial photographs, albeit from a different region (Andreassen and others, 2008).

267 We do not have any high-resolution digital aerial photography from the same year as our new

268 2014 inventory, but a comparison to aerial photographs from 2011 (Fig. 3c) shows it to be very

269 accurate. We therefore estimate a similar error to the 1988 and 2001 inventories that was used

270 in previous studies outlined above (i.e. ±3%).

271 Our estimates of error for the LIA areas based on the previously published moraine

272 mapping and dating from Ballantyne (1990) are subject to much larger uncertainties (in both

273 dating and in the extrapolation of glacier areas), which are difficult to quantify. Indeed, because

274 we simply extrapolate the 1955 inventory outlines to the moraine limits in the lower parts of

275 the glacier, it is likely that the ca. 1915 and ca. 1750 areas are simply lower-bound estimates,

276 with the upper-bound area unknown. In contrast, the length change measurements are much

277 more accurate and, given the size of the moraines, we estimate an error of ±30 m.

278

279 *3.4. Climate data*

280 There are no continuous long-term meteorological records from the Lyngen Peninsula

281 available. The nearest data are from Tromsø, located 40 km to the west (Fig. 1), which were

282 downloaded from the Norwegian Meteorological Institute (http://www.eklima.no/). Mean

283 monthly temperature data are available from September 1867 to December 1926 from station

284 #90440. This station was superseded by a new station (#90450) that has a record of mean

285 monthly temperatures from July 1920 to present. A comparison between the overlapping

286 monthly data between July 1920 and December 1926 revealed non-systematic differences

287 typically <0.5 °C. Following Andreassen and others (2012b), who also used these data, we took

288 the mean of the differences for all overlapping months to adjust the older data prior to July

289   1926. This gave a continuous monthly record of temperature from September 1867 to May

290   2017. We used this to plot mean annual and seasonal temperature trends and anomalies, in

291   addition to decadal means. Given the latitude, and following Andreassen and others (2012b),

292   we define summer as from June to September and winter from October to May (see also Nesje

293   and others, 2009; Giesen and others, 2014). Mean monthly precipitation data are available from

294   July 1920 (station #90450) to present and we used these to calculate total annual and total

295   seasonal precipitation trends and anomalies.

296

297   4. RESULTS

298   *4.1. Glacier area changes*

299   Changes in total glacier area between the four inventories are shown in Figure 4 and

300   summarised in Table 1. Noting that 22 glaciers are missing, the glacier inventory from 1955

301   contains 126 glaciers with a total area of 113.9 ±5.7 km^2. Measurements of the same 126

302   glaciers in 1988 shows that they had decreased to 102.2 ±3.1 km^2, which is a reduction of -10%

303   (-0.3% a^{-1}). In 2001, the same 126 glaciers totalled 106.8 ±3.2 km^2, which is a slight increase

304   (+4.5%), but which falls within the measurement error (Fig. 4). In 2014, the total area for these

305   126 glaciers had reduced to 93.1 ± 2.8 km^2, which is a clear decrease of -13% (-0.9% a^{-1}) and

306   well outside the measurement error. In total, glacier area decreased by around -18% between

307   1955 and 2014. Figure 5 illustrates this retreat at several glaciers, including the largest on the

308   Lyngen Peninsula: Strupbreen.

309   Because the 1988, 2001 and 2014 inventories included an additional 22 glaciers that

310   were missing from the 1955 topographic maps and inventory (e.g. Fig. 2), the total glacier areas

311   for 1988, 2001 and 2014 are slightly higher, but show the same overall trends as for the sample

312   of 126 glaciers (Fig. 4). The total area of all 148 glaciers on the Lyngen Peninsula in 2014 was

313 95.7 ± 2.9 km^2. Individual glaciers in the 2014 inventory range in size from 0.005 km^2 (glacier

314 ID 292) to 8.871 km^2 (glacier ID 200: Strupbreen, Fig. 5), with a modal value (49% of glaciers)

315 falling in the size range >0.1 to 0.5 km^2 (Fig. 6) and with a median glacier size of 0.201 km^2.

316 For comparison, glaciers in 1955 ranged in size from 0.034 km^2 to 10.211 km^2 with a median

317 of 0.365 km^2 (Table 1).

318   The rates of glacier area change between each of the dates are summarised in Table 2,

319 which includes data from the small sample of glaciers with dated moraine sequences (Section

320 3.3). It should be noted that the minimal changes between 1750 and 1915 are a long-term (165

321 years) average that masks any short-term fluctuations in glacier area over this period, but for

322 which we have no data.

323

324 *4.2. Glacier length changes*

325   Glacier length changes were able to be extracted for 10 glaciers with dated moraine

326 sequences and the results are summarised in Table 3 (see also Fig. 3). As noted above, the low

327 retreat rates between the 1750 and 1915 moraines likely mask possible short-term fluctuations

328 for which we have no evidence. Length changes between 1915 and 1955, however, indicate

329 higher mean rates of retreat (-17.4 m a^{-1}). Between 1955 and 1988, however, the mean retreat

330 rate halved to 9 m a^{-1} and one glacier (ID number 256: Blåisen) showed a small advance. The

331 mean retreat rate dropped again for the period 1988 to 2001 (-5.1 m a^{-1}), when six glaciers

332 retreated, two showed a slight advance and two exhibited no overall change. From 2001-2014,

333 all glaciers underwent retreat and the mean rate of change increased to -8.9 m a^{-1}. Thus, it is

334 interesting to note that whilst the period 2001 to 2014 was characterised by the highest rates of

335 areal shrinkage for a large sample of glaciers (Table 2), the period 1915 to 1955 was

336 characterised by the highest rates of terminus retreat for a small sample of the largest glaciers

337 (Table 3).

338

339 *4.3. Climatic trends*

340 Mean annual temperatures were generally low from 1870 to 1920, but show a clear increase

341 from the early 1920s to around 1940 (Fig. 7a). Mean annual temperatures then show a slight

342 decrease from the 1940s to the late 1980s, before a clear increase through to 2016 (Fig. 7a).

343 These broad trends are seen in both the mean annual (fig. 7a), mean winter (Fig. 7b) and mean

344 summer temperatures (Fig. 7c), and the mid-1990s onwards have seen a large number of

345 positive summer temperature anomalies (Fig. 7d). Indeed, decadal mean temperatures have

346 increased by around 0.5 °C per decade since the 1980s (Fig. 8). Precipitation trends are less

347 clear (Fig. 9), but total annual precipitation shows a generally increasing trend from the 1920s

348 to 1950s (Fig. 9a), followed by generally lower precipitation totals through the 1950s to 1980s

349 and then an increase from the mid-1980s, before slightly decreasing again from the mid-2000s.

350 This pattern is strongest in the winter precipitation totals (Fig. 9c) and is reflected in several

351 positive winter precipitation anomalies from the mid-1980s to late-1990s (Fig. 9d). Summer

352 precipitation totals (Fig. 9b) show a broadly similar trend and we note the decline in summer

353 precipitation totals since the mid-2000s.

354

355 *4.4. Topographic controls on glacier area change (1955-2014)*

356 The spatial pattern of glacier area loss between the 1955 and 2014 inventories (overall ~18%)

357 is shown on Fig. 10. Both absolute area changes and percentage area changes are highly

358 variable and there are no obvious spatial patterns e.g. east- versus west-facing glaciers. Indeed,

359 an analysis of the mean percentage glacier area loss (1955-2014) according to aspect shows no

360 clear patterns, other than a lower areal shrinkage for glaciers facing SE (Fig. 11). This is

361 perhaps surprising, but the overall population of glaciers is dominated by those facing N (16%),

362 NE (28%) and E (18%), which is expected (Evans, 2006). There is, however, a general trend

363 whereby larger glaciers have tended to decrease more in absolute area (Fig. 10b), but less in

364 relative (percentage) terms. A simple linear regression between glacier area in 1955 versus

365 absolute area change (1955-2014) gives an r^2 value of 0.47 (Fig. 12a), which is highly

366 significant (p <0.0001) despite the large scatter for smaller glaciers. When glacier area is

367 plotted against the percentage area change, however, the relationship is reversed (Fig. 12b),

368 such that larger glaciers lost a smaller percentage of their area in 1955 compared to smaller

369 glaciers. The r^2 value is very low (0.05), but significant (p = 0.01). A similarly weak (r^2 = 0.09)

370 but significant (p = 0.0007) relationship also indicates that glaciers at lower elevations have

371 tended to shrink more in absolute terms than those at higher elevations (Fig. 12c), but there is

372 no significant trend in percentage terms (Fig. 12d). A much stronger (r^2 = 0.21) and significant

373 (p <0.001) relationship is seen when the maximum glacier elevation is plotted against

374 percentage change (Fig. 12f), but there is no clear trend between maximum elevation and

375 absolute area change (Fig. 12e). Glaciers with steeper slopes have also tended to retreat less,

376 in absolute terms, than those with gentler slopes (Fig. 12g), and this relationship (r^2 = 0.21) is

377 significant (p <0.0001), but there is no clear trend in percentage terms (Fig. 12h). Note that we

378 use glacier topography data from the 2001 inventory (Andreassen and others, 2001a) in the

379 above analysis because topographic data for the 1955 inventory are not reliable. Also note that

380 similar trends to those shown in Fig. 12 are found when glacier changes between 2001 to 2014

381 are analysed.

382

383 **5. DISCUSSION**

384 *5.1. Temporal trends in glacier area change and potential climate forcing*

385 We first discuss our temporal data on glacier change in light of broad trends in climate data,

386 but it is important to note that changes in glacier area result from the interaction of surface

387 lowering, which is dictated by glacier mass balance, and the distribution of glacier thickness,

388 which is also influenced by local topographic setting. As such, glacier area changes are only

389 indirectly linked to the climatic controls on glacier mass balance but, averaged over large

390 samples and decadal time-scales, they are likely to reflect regional and long-term changes in

391 climate forcing.

392

393 *5.1.1. Little Ice Age maxima to 1955*

394   Previous work on the Lyngen Peninsula documented two prominent phases of glacier

395 expansion during the Little Ice Age that were dated to around the mid-18th century (1750s) and

396 the period 1910-1920 (Ballantyne, 1990), and which we generalise to ca. 1750 and ca. 1915

397 (see Section 3.3). Ballantyne (1990) noted that for most of the 21 glaciers he studied, the 1915

398 advance appears to have exceeded the ca. 1750 limits, and that only larger glaciers that

399 descended to lower elevations were more extensive in the 1750s, and only by a few tens of

400 metres (e.g. Fig. 3). Our measurements of a small sample (n = 10) of glaciers confirms this

401 pattern and shows that, overall, glacier areas decreased by only ~3% between ca. 1750 and ca.

402 1915 (Table 2; Fig.'s 3 & 5). It is important to note, however, that we have no data on possible

403 short-term fluctuations during the intervening 150 years or so, e.g. it is not clear how far they

404 may have retreated after ca. 1750 before readvancing to their most recent maximum ca. 1915.

405 That said, cumulative length change records from glaciers in southern Norway indicated very

406 minor and steady retreat from the 1750s to early 1900s (Nesje and others, 2008), which is

407 consistent with the available data from Lyngen and suggests minimal area change between ca.

408 1750 and ca. 1915.

Several workers have noted that the glacier expansion culminating ca. 1915 was largely driven by cooler temperatures (Whalley and others, 1989; Ballantyne, 1990; Bakke and others, 2005). Indeed, air temperature records clearly indicate that the last few decades of the 1800s and the first two decades of the 1900s were around 1.5 °C cooler than present (Fig. 7a), and that this cooling was most pronounced in the summer, when negative air temperature anomalies dominated from the start of the record (1867) to ca. 1920 (Fig. 7d). Following the most recent maximum ca. 1915, our results show that glaciers had retreated by 1955. Only 18 glaciers could be reconstructed at their 1915 moraine limits, but all of these glaciers were smaller in 1955, equating to a total areal loss of ~11% at -0.3% a^{-1} (Table 2). This reduction in area is consistent with air temperature trends, which show a clear and rapid warming throughout the 1920s, 1930s and 1940s (Fig. 7), known as the 'Early Twentieth Century Warming' event (Hanssen-Bauer and Nordli, 1998). Indeed, the 1930s was the third warmest decade on record (Fig. 8) and 1938 was second only to 2011 as the warmest year on record at Tromsø. We also note that the largest decreases in glacier length occurred during the 1915-1955 epoch, with mean retreat rates of 17.4 m a^{-1} and with a maximum of 29.6 m a^{-1} (Table 3). A similar finding was reported by Winsvold and others (2014) who noted that the highest retreat rates between their 1900 and 1950 inventories were experienced by five ice caps in northernmost Norway (western Finnmark). We note that winter precipitation was also steadily increasing during the 1930s and 1940s (Fig. 9), but this was clearly insufficient to offset the strong warming trend and glacier shrinkage.

5.1.2. 1955 to 1988

Data from 1955 onwards include a much larger sample of glaciers (n = 126). The total areal extent of these glaciers in the 1955 inventory was 113.9 ±5.7 km^2, but this had decreased to 102.2 ±3.1 km^2 in the 1988 inventory (Table 1, Fig. 4). This amounts to a total areal loss of

434 around -10% and the long-term rate of change (0.3% a^{-1}) is very similar to the previous epoch

435 (1915-1955). This areal loss and rate of change is also similar to that calculated from the retreat

436 of glaciers in the Jostedalsbreen region of SW Norway (i.e. 10%, or 0.33% a^{-1}) between 1966

437 and 2006 (Paul and others, 2011). The decrease in glacier area on Lyngen is also consistent

438 with the nearest reconstructed mass balance record at Langfjordjøkelen, which lies ~100 km

439 north-east of our study area (Andreassen and others, 2012b). The reconstructed mass balance

440 from 1948/49 to 1988/89 indicates that only 5 years had a positive mass balance >0.3 m water

441 equivalent (w.e.), and that the majority of years (n=25) had negative balances of < -0.3 m w.e.

442 This pattern is also broadly similar to the mass balance of a sample of 7 glaciers spread

443 throughout Norway, 6 of which experienced negative mass balances from the 1960s to the

444 1990s (Andreassen and others, 2002).

445   Although precipitation was generally decreasing from the mid-1970s to late 1980s (Fig.

446 9), and this may explain some of the reduction in glacier area, there are no strong trends in air

447 temperature and precipitation, which is perhaps surprising given the decline in glacier areas

448 between 1955 and 1988. However, the decrease in area might be explained by the fact that

449 some glaciers were still adjusting to the strong warming trend from the 1920s to 1940s,

450 particularly the larger glaciers with longer response times. Indeed, the relatively late LIA

451 maximum (ca. 1915) resulted in some glaciers with extensive areas at low elevations, which

452 would take several decades to retreat (cf. Nesje and others, 2008). A similar result was reported

453 in Andreassen and others (2000) who found that the highest rates of recession in northern

454 Norway occurred in the interval ca. 1900 to ca. 1950, but with most glaciers also retreating

455 between ca. 1950 and ca. 1980. Indeed, our measurements of glacier length changes on a small

456 sample of some of the larger glaciers (Table 3), indicate that the 1955-1988 epoch experienced

457 relatively high retreat rates (-9 m a^{-1}), although not as high as the 1915-1955 epoch.

458   Our measurements of glacier length changes are very similar to those calculated in

459   previous work that used high resolution aerial photographs from the early 1950s and field

460   measurements in the 1970s and 1980s (Gordon and others, 1986; 1995), giving us confidence

461   in our remote sensing analysis (cf. Paul and others, 2011). Gordon and others (1995), for

462   example, used the spacing of annual moraine ridges to estimate retreat rate of Sydbreen, which

463   was around 12-19 m a^{-1} between 1973 and 1980, but then dropped to between 6 and 9 m a^{-1} in

464   the early 1980s. This compares well with our long-term average rate of 19.3 m a^{-1} between

465   1955 and 1988 for the same glacier. At Steindalsbreen, monitoring of the glacier front position

466   since 1976 by one of the authors (GC) shows slightly lower retreat rates, falling from around

467   10-12 m a^{-1} before 1987 to about 7 m a^{-1} in 1988 (Nilsen, 2016).

468

469   *5.1.3. 1988 to 2001*

470   The period 1988 to 2001 is noteworthy because the total glacier area (n=126) showed a small

471   increase of +4.6 km^2 (Table 2). When the uncertainties from both the 1988 and 2001 inventory

472   are taken into account, this +4.3% increase lies within the measurement error, but it is similar

473   to the increase in area reported by Winsvold and others (2014) for a larger sample of glaciers

474   in northern Norway over a similar time period (+4.7%). Closer inspection of our data for

475   individual glaciers indicates variable behaviour, but 70% of the glaciers (n = 126) increased in

476   area between 1988 and 2001 and the mean percentage area increase of these was 22% (median

477   10%), which clearly indicates a predominance of growth over shrinkage. This is perhaps

478   surprising given that a warming trend is apparent from the early 1990s (Fig. 7 & 8), but there

479   is a noticeable increase in precipitation from the mid-1980s to the early 2000s (Fig. 9).

480   Moreover, this is a period when maritime glaciers elsewhere in Norway experienced positive

481   mass balances and were known to advance as a result of enhanced winter precipitation (e.g.

482   Nesje and others, 2000, 2008; Andreassen and others, 2005; Engelhardt and others, 2013).

483 Positive mass balances were also measured at eastern outlet of Langfjordjøkelen in the early

484 1990s, but the average value for the glacier over the period 1989-1995 (including modelled

485 values for 1994 and 1995) remained slightly negative (-1.1 m w.e.: Andreassen and others,

486 2012b; Andreassen and others, 2016).

487 It is also possible that enhanced winter precipitation in the 1990s could have resulted

488 in the presence of more late-lying snow patches on and around glaciers on the Landsat image

489 from 20th August 2001, which might have been misclassified as glaciers. However, winter

490 precipitation in 2000-2001 was not particularly high (and was below the 1971-2000 mean) and

491 summer temperatures in 2001 were almost 1°C above the 1971-2000 mean. Thus, we suggest

492 that many glaciers increased in area as a result of the increased precipitation from the mid-

493 1980s to early 2000s, but this pattern was not ubiquitous and the response of individual glaciers

494 was likely modulated by their local geometry and topography (see Section 5.2).

495 Measurement of glacier length change on a sample of ten glaciers also indicates variable

496 advance and retreat with no clear overall trend (Table 3). Some large glaciers like

497 Steindalsbreen, Strupbreen and Koppangsbreen show a pattern of overall retreat between 1988

498 and 2001 (averaging between -5 and -15 m a^{-1}), but this does not preclude minor advances over

499 shorter time-scales. For example, minor advances were recorded by NVE at Strupbreen and

500 Koppangsbreen between between 1984 and 1988, but both glaciers showed overall retreat

501 between 1988 and 2001 (Hausberg and Andreassen, 2009). Likewise, a small moraine ridge

502 has been linked to a minor advance of the terminus of Steindalsbreen between 1982 and 1985,

503 during a period (1976-1987) when the overall retreat averaged 10-12 m a^{-1} (Nilsen, 2016).

504 Thus, our measurements of length change are consistent with the overall pattern of areal

505 change, with some glaciers showing no obvious change in terminus position and others

506 showing a slight increase in length between 1988 and 2001. This variability of both advance

507 and retreat is similar to measurements of net frontal change of glaciers in northern Norway for

508   the period 1980-1998 (Andreassen and others, 2000), and is consistent with area changes in

509   Jostedalsbreen for the 1980s and 1990s (Paul and others, 2011) and the Svartisen region

510   between 1968 and 1999 (Paul and Andreassen, 2009). Notably, glacier recession was more

511   widespread in the Jotunheim region of southern Norway over a similar time period (Andreassen

512   and others, 2008), suggesting that glaciers in more maritime regions benefitted more from the

513   enhanced precipitation during the mid-1980s and 1990s than their more continental

514   counterparts (see also Andreassen and others, 2005; Nesje and others, 2000; 2008).

515

516   *5.1.4. 2001 to 2014*

517   The period 2001 to 2014 shows a very clear signal of shrinkage and the total glacier area

518   decreased by around -14 km^2 or -13%. This equates to the highest reduction in area of any of

519   the epochs we measured (Table 2) and indicates an average shrinkage of -1% a^{-1}. A similar

520   acceleration in areal loss from the early 2000s has also been identified across many other

521   regions of Norway (Nesje and others, 2008; Paul et al, 2011; Winsvold and others, 2014;

522   Andreassen and others, 2016). Our measurements of length changes also indicate a clear pattern

523   of retreat and an acceleration in the mean retreat rate from -5.1 m a^{-1} (1988-2001) to -8.9 m a^{-}

524   ^{1} (2001-2014). Similar rates of retreat for the period 2011-2014 have been measured in the field

525   at Sydbreen (-12.3 m a^{-1}) and Steindalsbreen (-11 m a^{-1}) (Kjøllmoen and others, 2016). Not

526   surprisingly, this acceleration in retreat coincides with a strong warming trend since the 1990s

527   (Fig. 8), particularly in winter, but also in summer (Fig. 7). The 2000s were >1.5 °C warmer

528   than the 1900s and 1910s, and the rate of warming since the 1980s is around 0.5 °C per decade

529   (Fig. 8). Moreover, this strong warming trend has been accompanied by a decrease in both

530   summer and winter precipitation since the early 2000s. Thus, the combination of increased

531   temperatures and decreased precipitation between 2001 and 2014 has led to a marked

532   acceleration in glacier shrinkage. Field observations from Steindalsbreen (Fig. 13) suggest that

22

533   the rate of retreat is continuing. The length change extracted from our inventories in 2001 and

534   2014 averaged -15.6 m a^{-1}, and field measurements in September 2017 indicated a further -120

535   m of retreat between the 2010 marker-post and the glacier's terminus, equating to -17.1 m a^{-1}

536   over those 7 years. This retreat is likely to be accelerated by the growth of a proglacial lake in

537   front of the terminus that is forming in an overdeepening cut into bedrock below the icefall

538   (Fig. 13).

539   The strong climatic warming post-2000s is also evident in the nearest measured mass

540   balance record of Langfjordjøkelen. Mass balance measurements since 1989 show an

541   increasingly negative cumulative mass balance since the mid-1990s, primarily driven by an

542   increasingly negative summer balance, but also by winter balances that are becoming less

543   positive (Andreassen and others, 2012b). Indeed, the sensitivity of the annual mass balance to

544   a 1°C warming is -0.76 m w.e., whereas a 10% increase in precipitation would only result in

545   +0.2 m w.e. (Andreassen and others, 2012b). Put another way, precipitation would have to

546   increase by 40% to compensate for a 1°C warming. Elsewhere in Norway, mass balances

547   modelled from a temperature-index model indicate a dramatic decrease in both summer and

548   winter balances between 2000 and 2010 that is unprecedented in the previous four decades

549   (Engelhardt and others, 2013).

550

551   *5.2. Topographic controls on glacier retreat*

552   Whilst the climatic trends identified above have governed the broad patterns in glacier change,

553   it is clear that the response of individual glaciers is modulated by their local topographic setting

554   and geometry. As expected, the strongest significant relationship is between glacier size and

555   absolute area loss (Fig. 12a), which has been reported in several studies from other mountain

556   regions (e.g. Granshaw and Fountain, 2006; Paul and others, 2011; Stokes and others, 2013).

This is because larger glaciers tend to descend to lower elevations where gently-sloping tongues are more sensitive to climate warming, i.e. only a small increase in the ELA can rapidly increase the ablation area. However, and as noted above, this relationship is reversed when area change is expressed as percentage loss, indicating that although smaller glaciers lose less ice in absolute terms, it is often a much larger proportion of their area (Fig. 12b). This relationship is very weak ($r^2 = 0.05$), and shows a similarly large scatter to other regional studies of glacier change in Norway (e.g. Baumann and others, 2009; Paul and others, 2011), but it is statistically significant ($p = 0.01$). Very small glaciers (e.g. <0.5 km^2) are more susceptible to radiation from surrounding terrain (Demuth and others, 2008) and they tend to have higher volume-to-area and perimeter-to-area ratios, which makes them shrink faster than larger glaciers for any given ablation rate (Granshaw and Fountain, 2006). That said, the large scatter in the response of smaller glaciers (Fig. 12b) likely reflects the fact that some are located in topographically favourable locations (e.g. sheltered cirques fed by wind-blow snow) that allows them to survive longer than might otherwise be the case (Kuhn, 1993; De Beer and Sharp, 2009; Paul and Andreassen, 2009; Stokes and others, 2013). Thus, whilst glacier size is a good predictor of absolute area change, it is a rather poor predictor of the percentage glacier area change, which suggests that other factors are modulating glacier recession.

Previous work on Lyngen emphasised the importance of high-elevation plateau-icefields as source areas for glaciers at much lower elevations, such that valley glaciers at low elevations are more likely to persist if they are connected to high-elevation source areas (Gellatly and others, 1986; Gordon and others, 1987, 1995; Whalley and others, 1989, 1995; Rea and others, 1999). Our dataset is based on a much larger sample of glaciers than previous work (typically limited to <10 glaciers) but clearly supports some of these earlier assertions. For example, one of the strongest significant relationships is between the maximum elevation of glaciers and the percentage area change (1955-2014), indicating that glaciers with high

582 elevation catchments have tended to show less shrinkage than those at lower elevations, and

583 that this relationship is significant (Fig. 12f). Gordon and others (1987) suggested that glaciers

584 with maximum altitudes below ~1,400-1,500 m had shown substantial ice loss and we note that

585 the median percentage change for glaciers with maximum elevations >1,400 m was just -9%

586 (n = 39), whereas it was -28% for those with maximum elevations <1,400 m (n = 86). Thus,

587 the importance of high elevation catchments and plateau-icefields perhaps explains why

588 maximum elevation is a much stronger predictor of glacier recession compared to the minimum

589 elevation of glaciers (Fig. 12c, d). It may also explain why glacier slopes show little

590 relationship with percentage area change (Fig. 12h). There is a tendency for glaciers with

591 gentler slopes to retreat more in absolute terms than those with steeper slopes (cf. Winsvold

592 and others, 2014), but this is likely to reflect the relationship between glacier size and slope (r^2

593 = 0.27), which is highly significant (p <0.0001), i.e. mean slopes tend to be lower on larger

594 glaciers which retreat more in absolute terms (Paul and others, 2011).

595

596 *5.3. Future evolution of glaciers on the Lyngen Peninsula*

597 Climate projections for the region suggest that summer temperatures will increase by around

598 2°C by 2021-2050, compared to 1961-1990 epoch (Hanssen-Bauer and others, 2015). Over the

599 same period, winter precipitation is likely to increase by around 10%, but there is much more

600 uncertainty (Hanssen-Bauer and others, 2015). Any increase in winter precipitation is likely to

601 make winter balances more positive, but increases in summer temperature are likely to make

602 summer balances much more negative and, importantly, extend the length of the ablation

603 season. In addition, increased temperatures will reduce the fraction of precipitation falling as

604 snow. Thus, any increase in precipitation will only partly counteract increased temperatures

605 and it is clear that glaciers will continue to retreat. The mass balance records from

606 Langfjordjøkelen suggest that this small ice cap is already far from an equilibrium state, with

607   7 of the 12 years (1998-2009) indicating that the eastern outlet had no accumulation area

608   remaining at the end of the summer (Andreassen and others, 2012b). This led Andreassen and

609   others (2012b) to speculate that the glacier may disappear completely within the next 50-100

610   years.

611   Our data suggest that numerous glaciers have already lost >50% (with some >80%) of

612   their area since 1955 and might disappear within the next 50 years, possibly within the next

613   decade. Previous work noted that some of the lower-most plateau-icefields on Lyngen (<1,500

614   m) had rapidly diminished from the early 1950s to 1980s (Gordon and others, 1987, 1995). For

615   example, Gordon and others (1995) reported that Bredalsfjellet (ID 236: maximum elevation:

616   ~1,400 m) was ~0.5 km^2 in 1953, but had reduced to 0.21 km^2 in 1979, and earlier work by

617   Gordon and others (1987) had predicted that it "might soon cease to exist" (p. 752). Our data

618   for the same glacier indicate an area of 0.47 km^2 in 1955, 0.16 km^2 in 1988, 0.17 km^2 in 2001,

619   and just 0.019 km^2 in 2014 (the fourth smallest in the inventory). This represents a 96%

620   decrease in area between 1955 and 2014 and an 89% decrease between 2001 and 2014,

621   indicating that the glacier is close to the threshold for viability and is likely to vanish in the

622   next few years, if recent climatic trends persist. Moreover, there are 17 glaciers in the 2014

623   inventory that are <0.05 km^2 and all of these have maximum elevations below ~1,400 m. Given

624   our data indicating that small glaciers with low maximum elevations are most vulnerable

625   (Section 4.4, Figure 12), it is not unreasonable to suggest that most, if not all, of these glaciers

626   will disappear in the next decade or so and be absent from future inventories. More generally,

627   Nesje and others (2008) also used the altitudinal difference between the maximum elevation

628   and the ELA, together with the size of the glacier, to assess glacier vulnerability to future

629   climate change throughout Norway. Using climate projections for the period 2071-2100 that

630   indicate an increased summer temperature of 2.3 °C and a 16% increase winter precipitation,

631   they suggested that glacier area is likely to be reduced by around 34% across mainland Norway

632   and that seven of the 34 largest glaciers are likely to have melted away by 2100.

633

634   **6. CONCLUSIONS**

635   This paper presents new data on glacier change on the Lyngen Peninsula, northern Norway,

636   using data from existing glacier inventories (1955, 1988, 2001) together with a new inventory

637   from 2014, and glacier limits reconstructed during the LIA (Ballantyne, 1990). The most recent

638   LIA maximum culminated around ca. 1915 was likely driven by cooler air temperatures in the

639   preceding four decades. Our results show that shrinkage from this position was widespread and

640   driven by a rapid warming trend in the 1930s and 1940s that resulted in an areal reduction of

641   around -11% by 1955 (-0.28% a^{-1}) and with length changes averaging -17.4 m a^{-1} (n = 9).

642   Analysis of a much larger sample of glaciers between 1955 and 1988 (n = 126) revealed further

643   areal shrinkage of around -10% (-0.31% a^{-1}) that was likely driven by a continued response to

644   the warming of the 1930s and 1940s, and a decrease in precipitation from the mid-1970s to late

645   1980s. Length changes for a small sample of glaciers (n = 10) averaged -9 m a^{-1} between 1955

646   and 1988. Between 1988 and 2001, however, the total glacier area increased by +4.3% (+0.33%

647   a^{-1}). This lies within the measurement error, but is consistent with records of enhanced winter

648   precipitation and occurred at a time when numerous maritime glaciers elsewhere in Norway

649   experienced positive mass balances (Nesje and others, 2000; 2008; Andreassen and others,

650   2005; Engelhardt and others, 2013). Measurements of glacier length changes (n = 10) also

651   revealed a mixture of both advance and retreat between 1988 and 2001.

652   By far the most rapid rates of areal shrinkage (~1% a^{-1}) occurred between 2001 and

653   2014, which saw a -13% reduction in total glacier area, which we link to declining precipitation

654   and a sharp increase in the rate of warming since the early 1990s. Indeed, the decade beginning

655 in 2000 was >1.5 °C warmer than the decade beginning in 1910, and the rate of warming since

656 the 1980s has been around 0.5 °C per decade. The new inventory for 2014 includes 148 glaciers

657 that occupy 95.7 km^2. If the areal shrinkage of a small sample of glaciers (n = 18) between the

658 LIA and 2014 is representative of the study region, then our results suggest that the total glacier

659 area on the Lyngen Peninsula has decreased by around -30% in the last century (ca. 1915-

660 2014), with most of the larger valley glaciers retreating -0.5 to -1.5 km over this period. The

661 response of individual glaciers is highly variable, but our analysis shows that small glaciers

662 with relatively low maximum elevations (~1,400 m) have decreased the most in terms of their

663 percentage loss since 1955 (with some losing up to 96%), and that these glaciers will be most

664 vulnerable to future climate change (cf. Nesje and others, 2009). Under realistic warming

665 scenarios of around 2 °C by 2050 (Hanssen-Bauer and others, 2015), we predict that several

666 (~20) small glaciers <0.05 km^2 that lie below ~1,400 m will disappear in the next few decades.

667 The terminus retreat of several of the larger glaciers will continue and, in some settings, this is

668 likely to lead to the further development of proglacial lakes that may have implications for

669 hydro-electricity generation and outburst floods.

670

671 **Data availability:**

672 Outlines from 1955, 1988 and 2001 are available from the CryoClim data portal

673 (www.cryoclim.net/) and from the GLIMS database (www.glims.org). The 2014 inventory will

674 also be submitted to GLIMS and is available from the lead author. Meteorological data are

675 available for download from www.eKlima.no.

676

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Tables:

Table 1: Comparisons between glacier inventory data for 1955, 1988, 2001 and 2014. Note that the 1955 inventory is missing 22 glaciers and so comparisons are made between extents for those glaciers (n = 126) and for extents for the full sample (n = 148).

	1955	1988	2001	2014
Total glacier area (km²)	113.9 (±5.7) n = 126	102.2 (±3.1) n = 126	106.8 (±3.2) n = 126	93.1 (±2.8) n = 126
	n.b. 22 glaciers missing	104.6 (±3.1) n = 148	109.9 (±3.3) n = 148	95.7 (±2.8) n = 148
Min. glacier area (km²)	0.034	0.009	0.018	0.005
Median glacier area (km²)	0.365	0.234	0.250	0.201
Max. glacier area (km²)	10.211	9.573	9.513	8.871

Table 2: Comparisons of rates of area change for each measurement epoch.

	1750-1915	1915-1955	1955-1988	1988-2001	2001-2014
Number of glaciers (n)	10	18	126	126	126
Total area change (km²)	-1.6	-5.8	-11.7	+4.6	-13.7
(%)	-3.4	-10.9	-10.3	+4.3	-12.8
Rate of change (km² a⁻¹)	0.001*	-0.15	-0.35	+0.35	-1.05
(% a⁻¹)	-0.020*	-0.28	-0.31	+0.33	-0.98

*note that these very low rates of change are simply a function of the long time-step between measurements and are likely to mask shorter-term variations in area but for which we have no evidence.

Table 3: Comparisons of length changes for each measurement epoch

	1750-1915*	1915-1955	1955-1988	1988-2001	2001-2014
Number of glaciers (n)	9	9	10	10	10
Min. retreat rate (m a⁻¹)	-0.2	-9.1	0.5	5.9	-0.8
Max. retreat rate	-1.1	-29.6	-19.3	-22.9	-21.3
Median retreat rate (m a⁻¹)	-0.5	-19.2	-12.0	-3.5	-8.6
Mean retreat rate (m a⁻¹)	-0.6	-17.4	-9.0	-5.1	-8.9

*note that these rates of change are derived from a long time-step between measurements and are likely to mask shorter-term variations in length but for which we have no evidence.
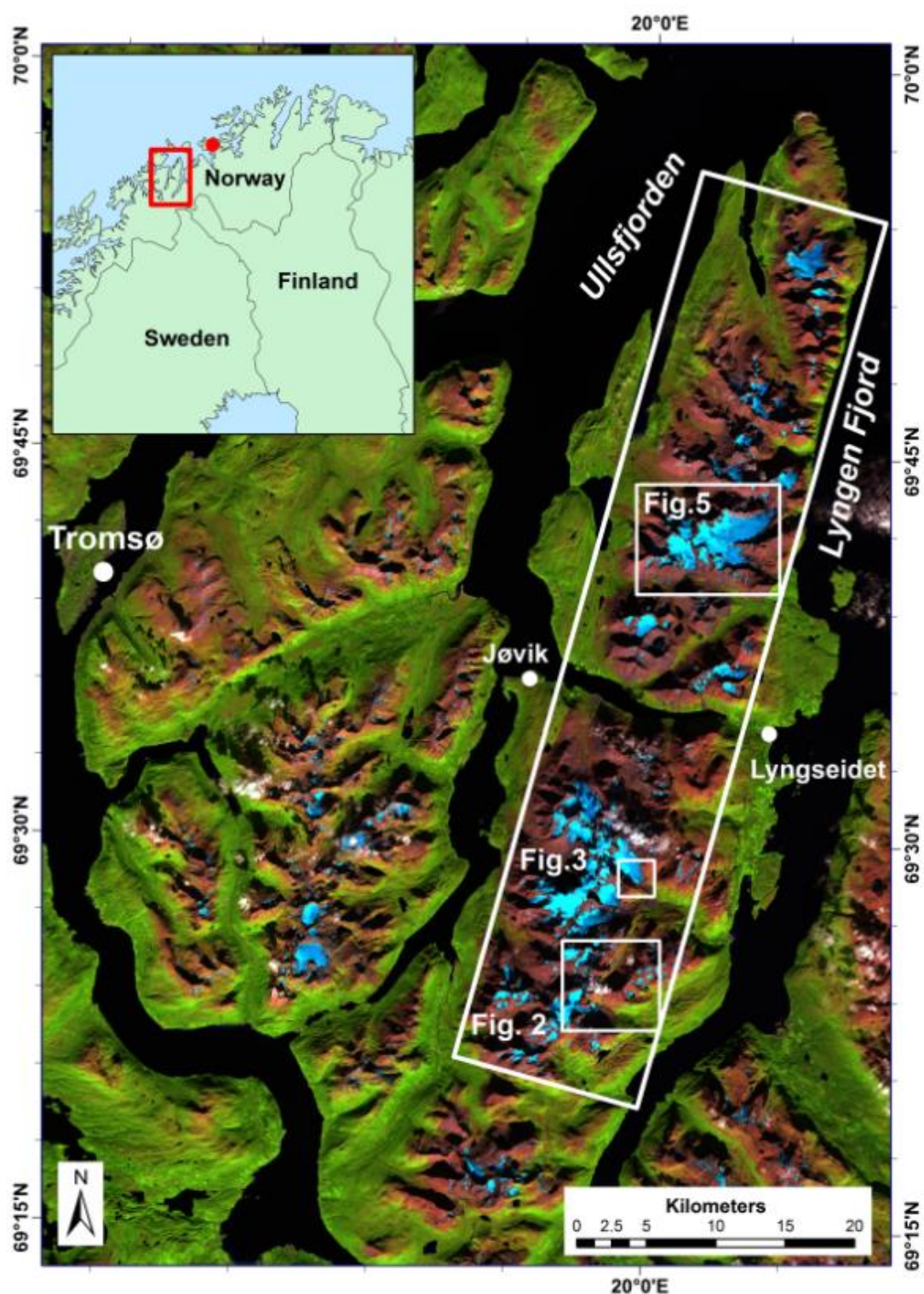
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878 **Figure 1:** Location of the Lyngen Peninsula in northern Norway on a false colour composite
879 Landsat 8 scene from 25th August 2014 (red, green, blue: bands 6, 5, 4). Glaciers appear as
880 bright blue with cloud as white and water black. The study area is shown within the large
881 white box and contains 149 glaciers in the 2001 Norwegian Glacier Inventory (Andreassen
882 and others, 2012a). The small red dot on the inset map shows the location of
883 Langfjordjøkelen, where the nearest mass balance measurements have been recorded
884 (Andreassen and others, 2012b).

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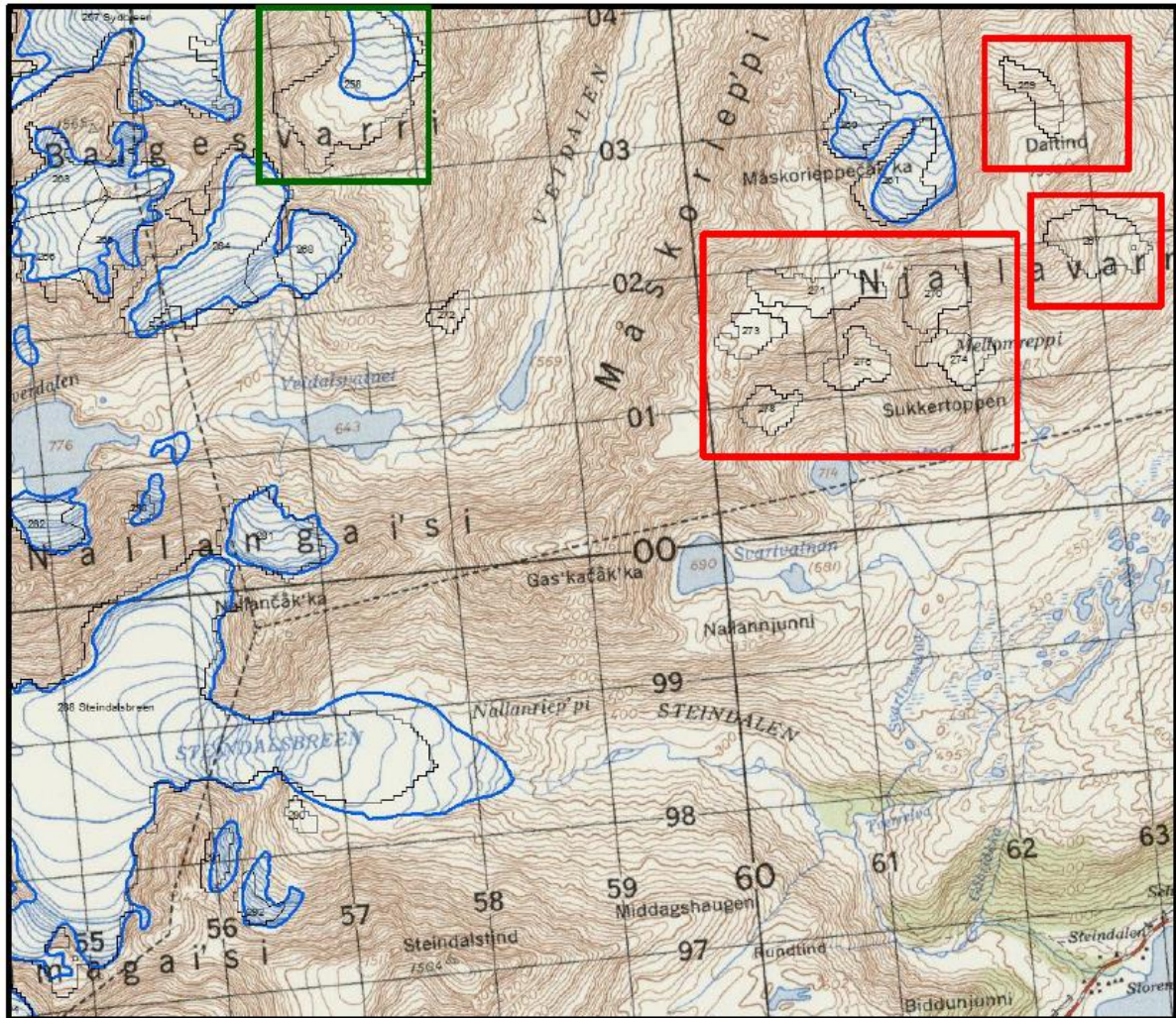
Figure 2: Glacier outlines on the Lyngen Peninsula (location shown on Fig. 1) digitised from
1:50,000 Norwegian Mapping Authority topographic maps dated to 1955 (blue lines) and
used by Winsvold and others (2014). Thin black lines show outlines from the 2001 inventory
(Andreassen and others, 212a). Note that some glaciers did not appear on the topographic
maps (red boxes) and that a very small number are much smaller than expected in their
accumulation areas (e.g. green box). For scale, grid squares are 1 km x 1 km. A field
photograph of Steindalsbreen (ID 288: bottom left) is shown in Fig. 13.

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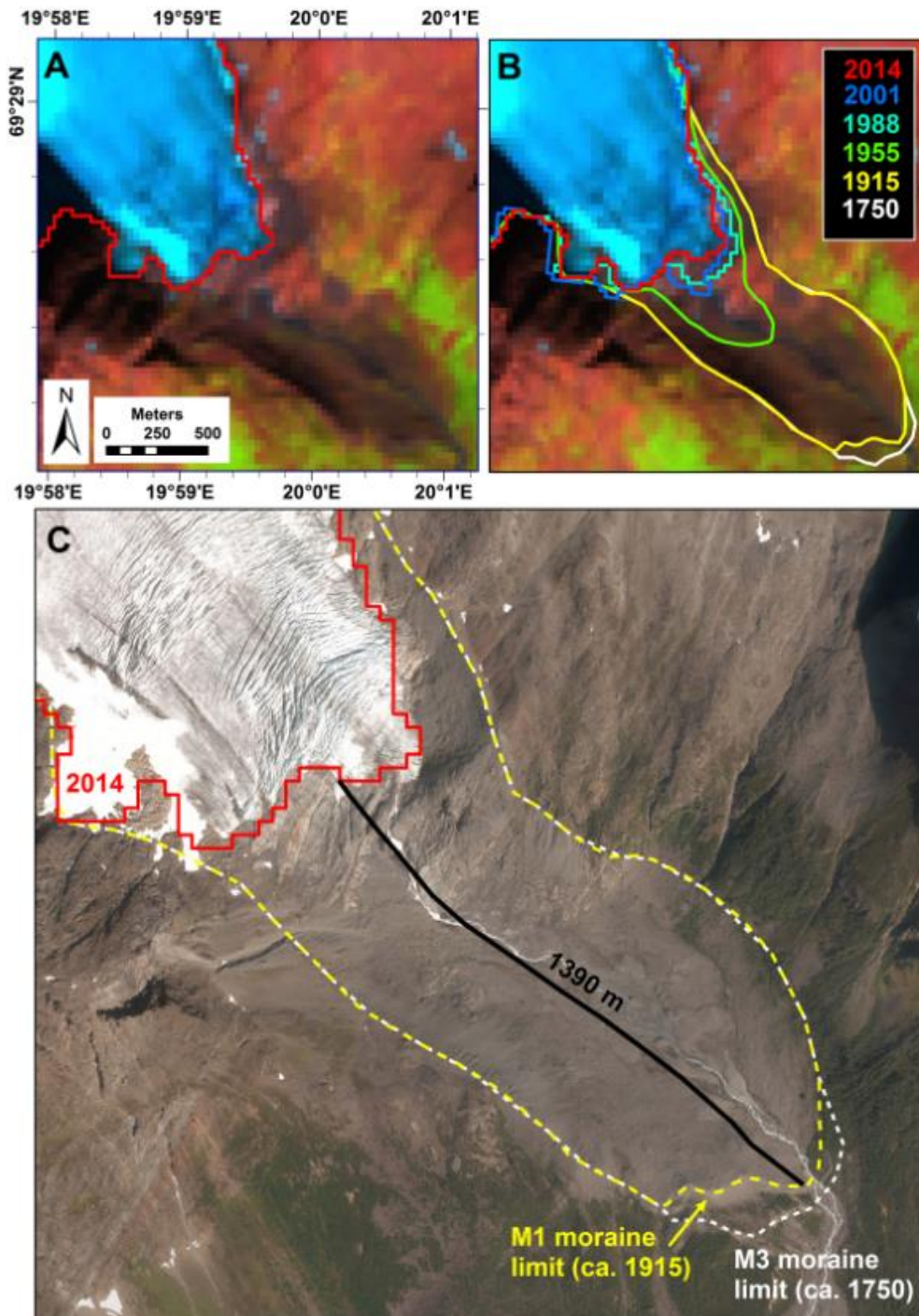
Figure 3: (**a**) Landsat 8 satellite image (RGB: 6,5,4) from 25th August 2014 showing the automatically derived outline (red line) of the terminus of Vestbreen (ID 240) based on a band 6/4 ratio image with a threshold ≥1.3. (**b**) Comparison between outlines from earlier inventories (2001, 1988 and 1955) and reconstructed limits from ca. 1915 and ca. 1750 based on moraine maps and dating from Ballantyne (1990). (**c**) Aerial photograph (from 2011; source: www.norgeinbilder.no) showing moraine limits and ages from Ballantyne (1990) that were used to extend the 1955 outlines to these older limits dated to ca. 1915 (M1 moraines) and ca. 1750 (M3 moraines). Also note the good correspondence between the Landsat-derived outline for 2014 (**a**) and the aerial photograph from 2011 (**c**). Location shown on Fig. 1.

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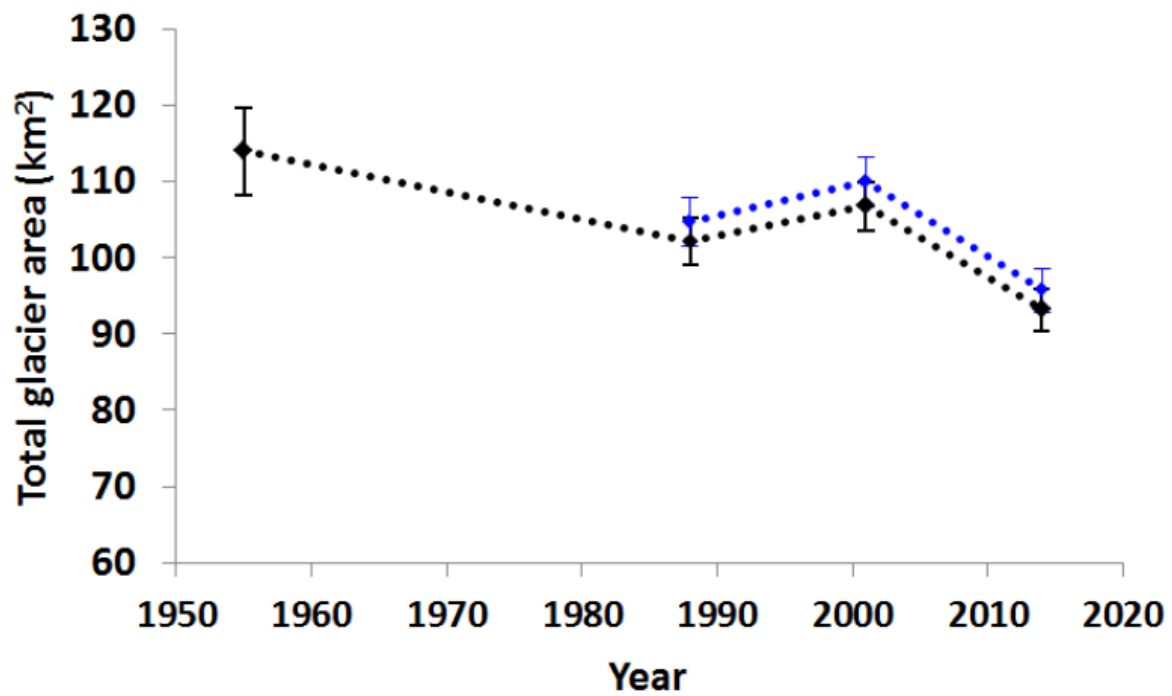
907 **Figure 4:** Total glacier area changes for all 126 glaciers included in the 1955 inventory
908 (black data points) and for the complete set of 149 glaciers that are included in the 1988,
909 2001 and 2014 inventories (blue data points). Note that the slight increase in area between
910 1988 and 2001 lies within the measurement error, but all other changes are outside the
911 measurement error.
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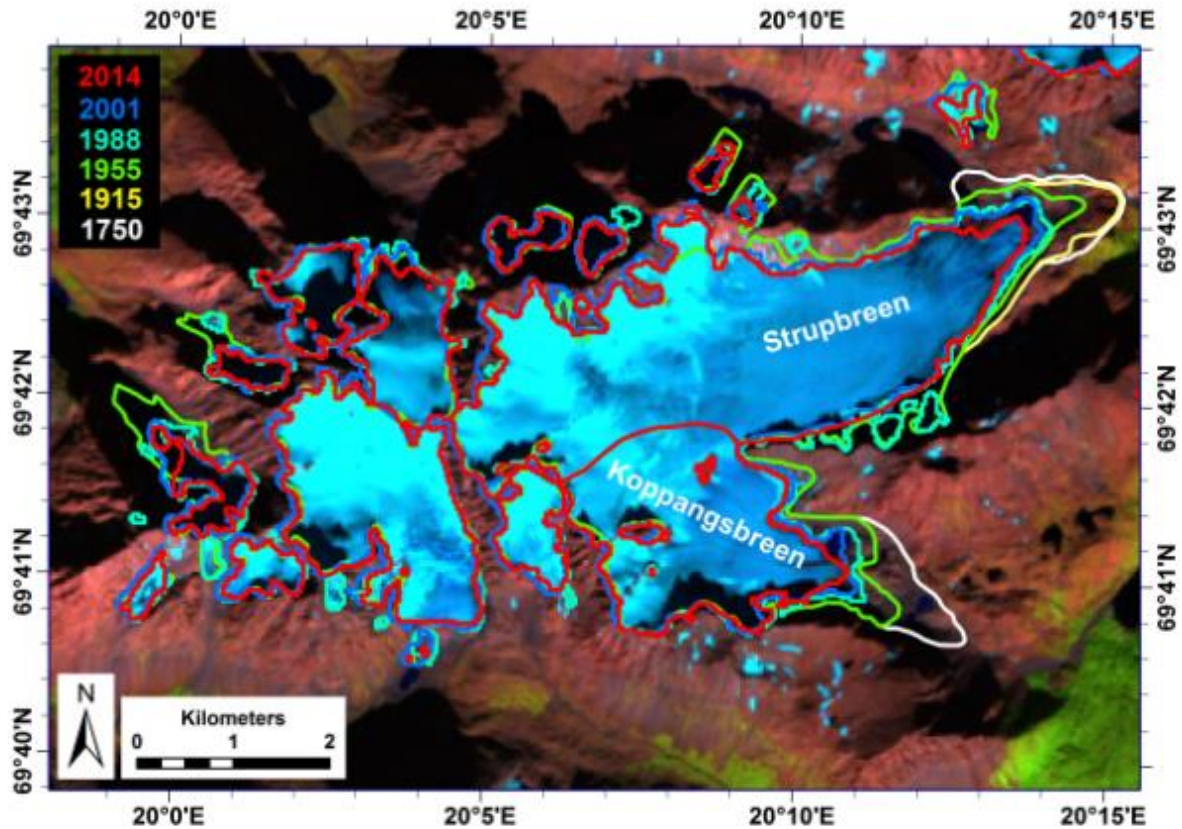
913
914 **Figure 5:** Landsat 8 satellite image (RGB, 6,5,4) from 25th August 2014 of a part of the study
915 area that includes Strupbreen (ID 200) and Koppangsbreen (ID 205) with glacier outlines
916 from 1750, 1915, 1955, 1988, 2001 and 2014 (location shown on Fig. 1). Reconstructed
917 limits from ca. 1750 and ca. 1915 are based on moraine maps and dating from Ballantyne
918 (1990). Note that he only studied Strupbreen and Koppangsbreen in this location and did not
919 map any moraines dated to ca. 1915 in front of Koppangsbreen.
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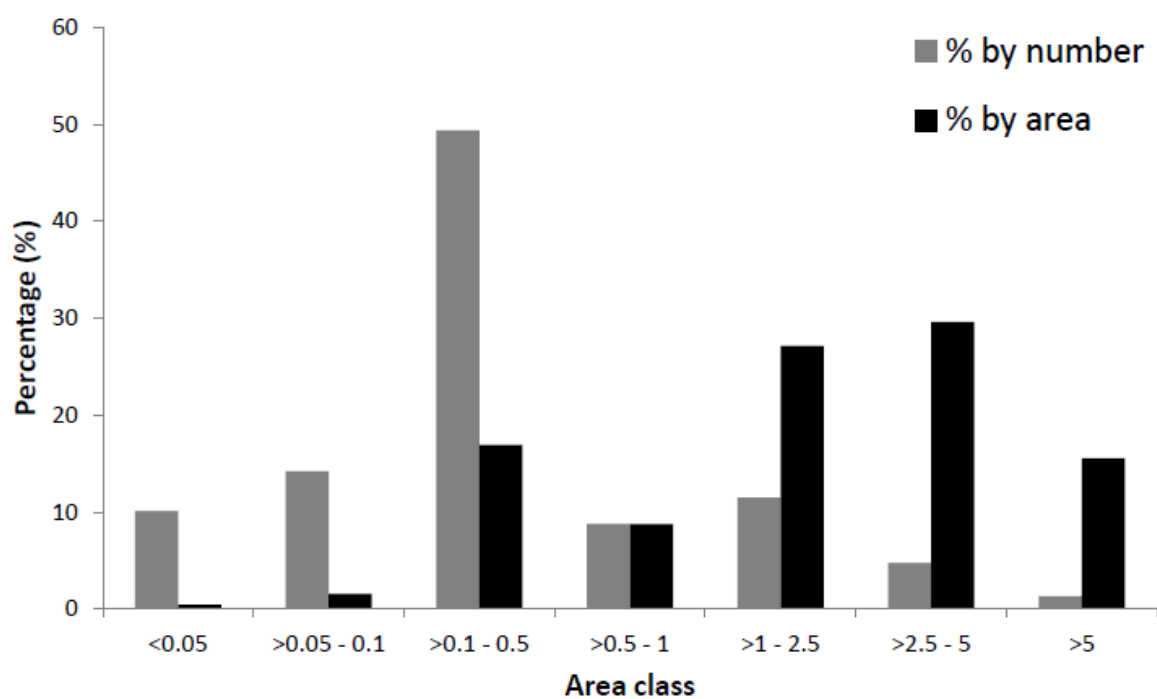
922 **Figure 6:** Percentage frequency of glacier number and area by glacier sizes in the new 2014
923 inventory of the Lyngen Peninsula (Fig. 1) (n = 148 glaciers).
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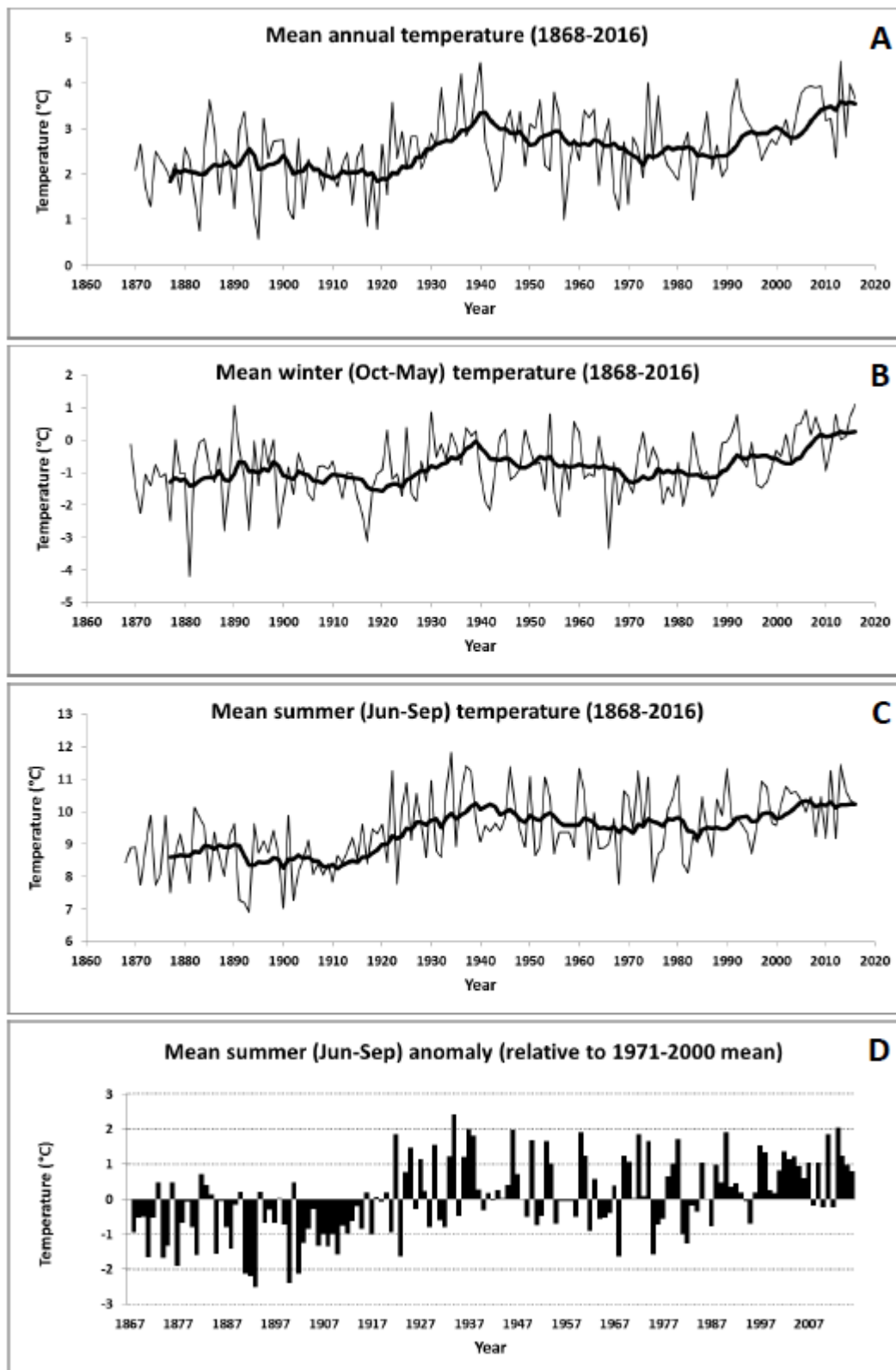
Figure 7: Mean annual temperature (**a**), mean winter (October to May) temperature (**b**),
mean summer (June to September) temperature (**c**) and mean summer temperature anomaly
relative to the 1971-2000 summer mean (**d**). Smoothed lines represent 10-year moving
average. Data from Tromsø (station #90440 and #90450: see Section 3.4) downloaded from
www.eklima.no.

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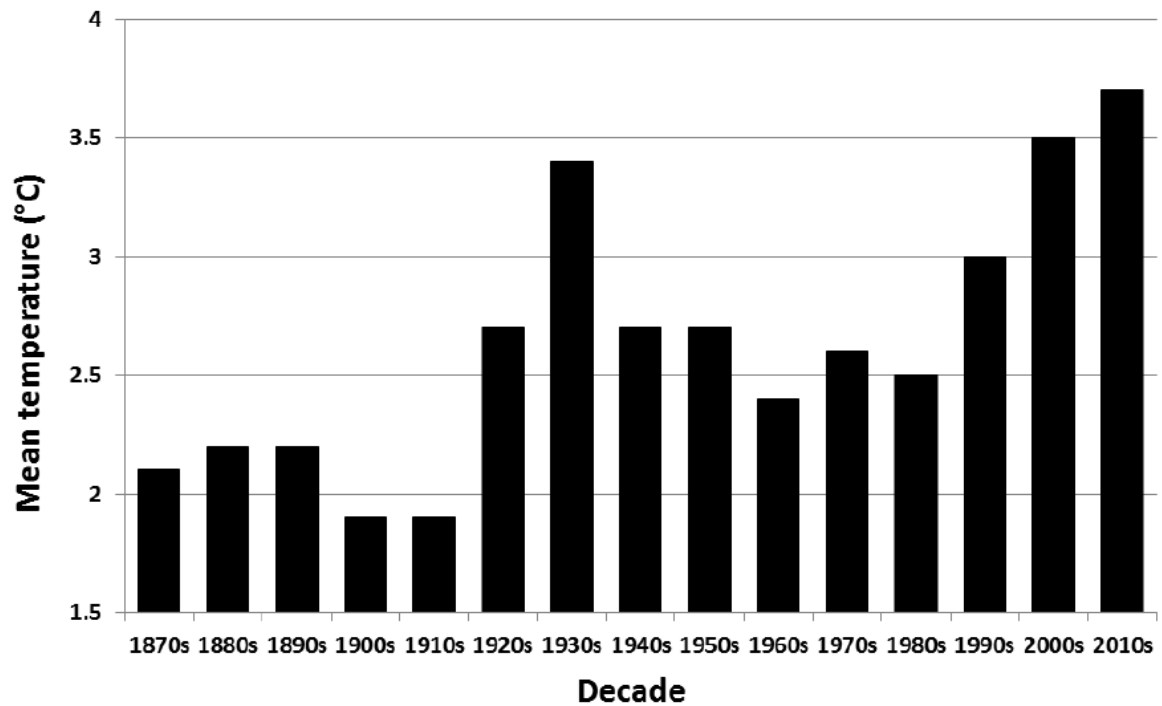
933 **Figure 8**: Decadal mean annual temperatures. Note that data from 2010 only include data up
934 to December 2016. Data from Tromsø (station #90440 and #90450: see Section 3.4)
935 downloaded from www.eklima.no.
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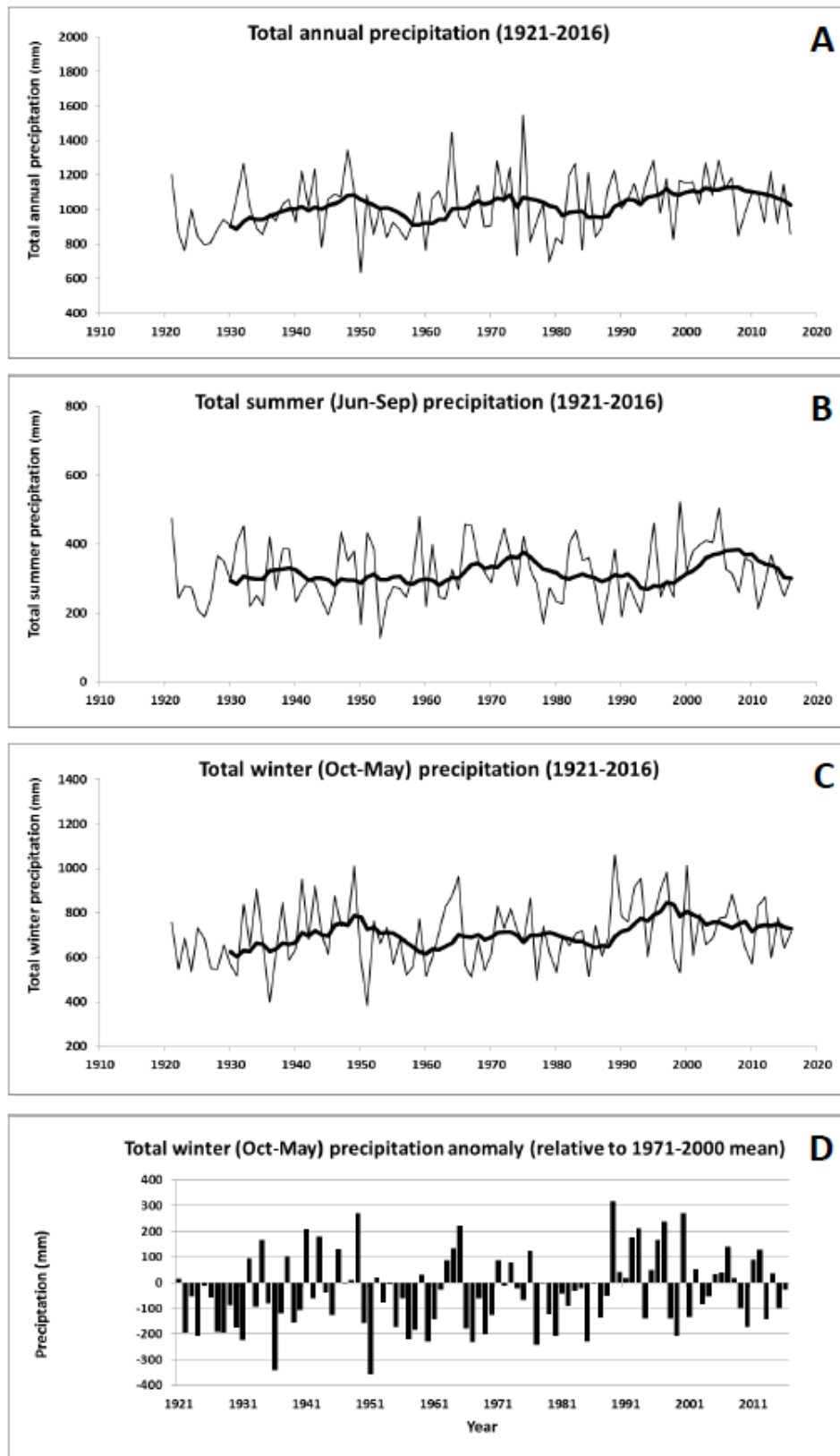
Figure 9: Total annual precipitation (**a**), total summer (June to September) precipitation (**b**) total winter (October to May) precipitation, (**c**) and total winter precipitation anomaly relative to the 1971-2000 winter mean (**d**). Smoothed lines represent 10-year moving average. Data from Tromsø (station #90450) downloaded from www.eklima.no.

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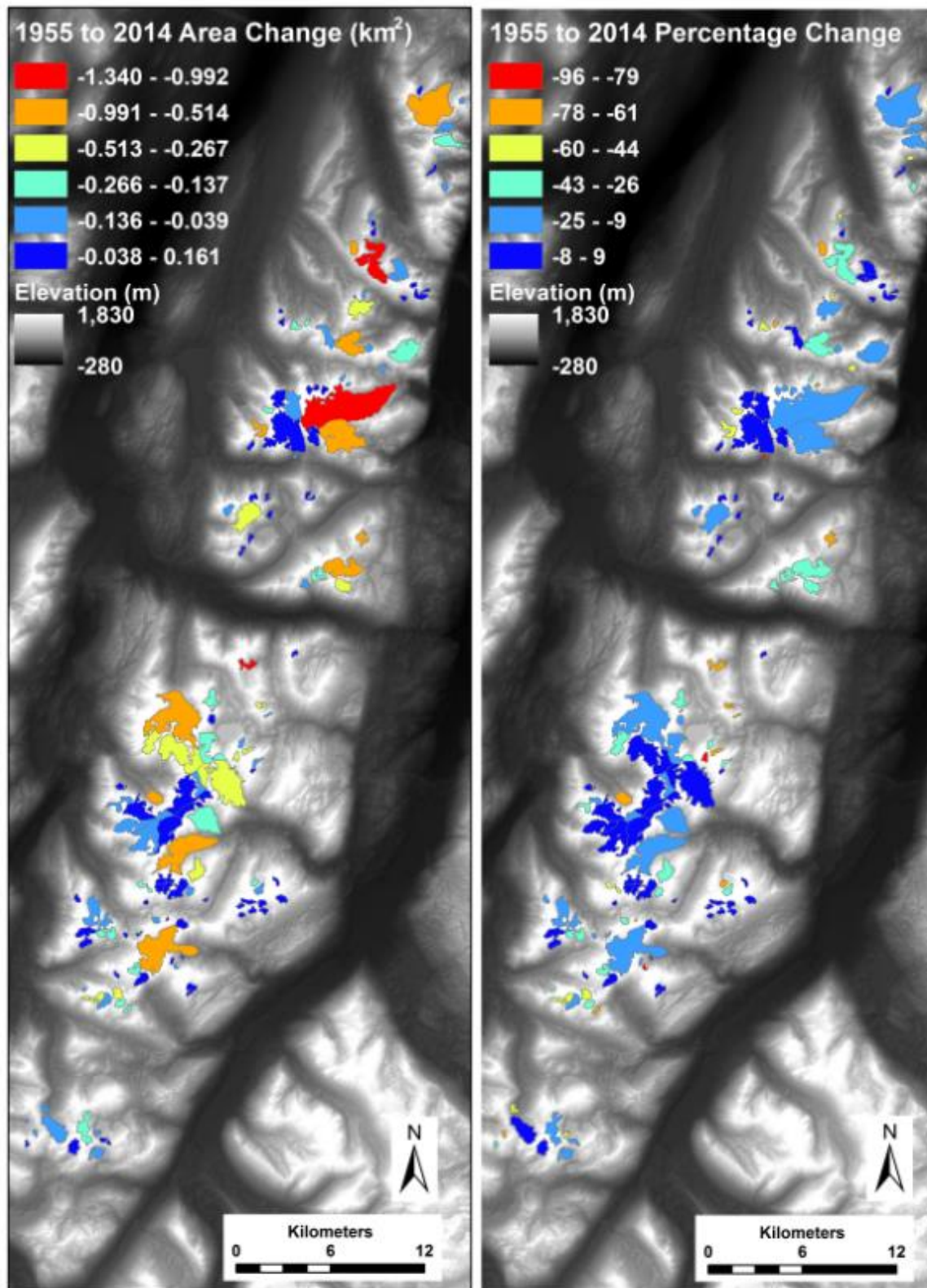
Figure 10: Colour coded map of: (**a**) glacier area change (km^2) from 1955-2014 and (**b**) percentage area change 1955-2014. Note the tendency for large glaciers to lose more ice in absolute terms (**a**), but less ice in relative (percentage) terms (**b**). Coordinates removed for clarity but see Fig. 1 for location.
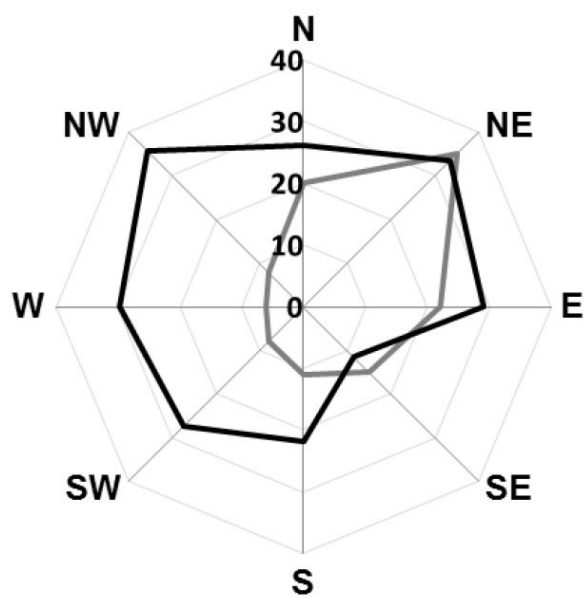
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Figure 11: Mean percentage areal loss from 1955 to 2014 according to aspect (black line), showing no obvious patterns. The number of glaciers within each aspect category is also plotted (grey line) and shows an expected dominance of glaciers facing N, NE and E.
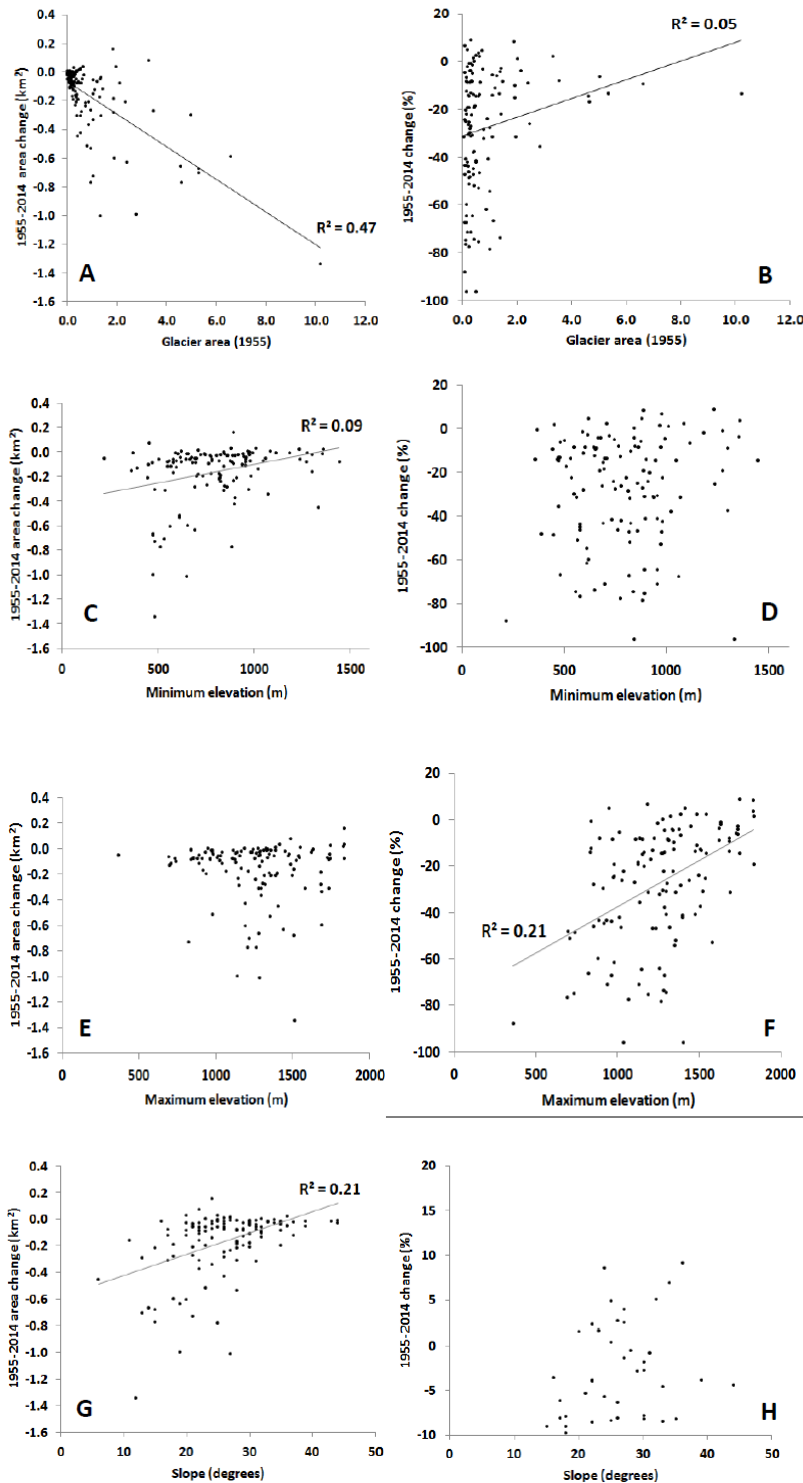
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Figure 12: Scatterplots of: (**a**) glacier area (1955) versus glacier area change (1955-2014); (**b**) glacier area (1955) versus percentage glacier area change (1955-2014); (**c**) minimum elevation (2001) versus glacier area change (1955-2014); (**d**) minimum elevation (2001) versus percentage glacier area change (1955-2014); (**e**) maximum elevation (2001) versus glacier area change (1955-2014); (**f**) maximum elevation (2001) versus percentage glacier area change (1955-2014); (**g**) slope (2001) versus glacier area change (1955-2014); (**f**) slope (2001) versus percentage glacier area change (1955-2014). Note that trendlines and R^2 values are only shown for statistically significant (p <0.05) relationships.

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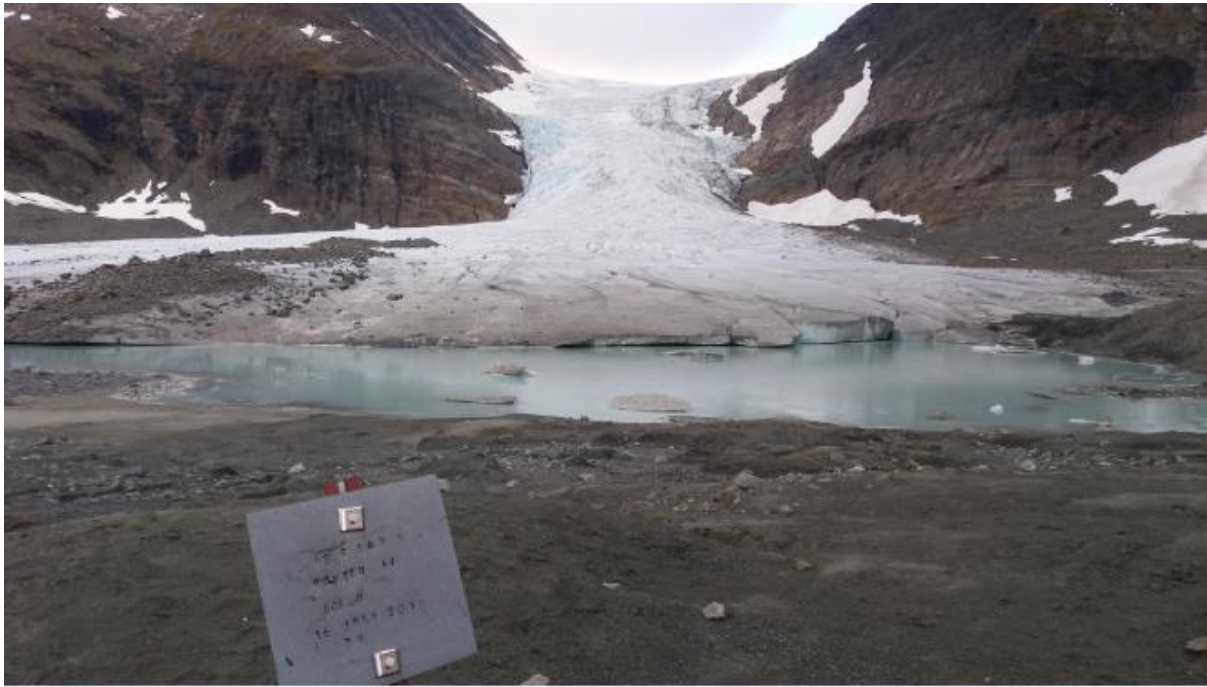
Figure 13: Field photograph of the terminus of Steindalsbreen (glacier ID 288: see also map
in Fig. 2) on 21st September 2017 taken from the position of the terminus in July 2010
(located by the marker post in the foreground). The terminus is now ~120 metres from the
terminus in 2010, equating to a retreat rate of 17.1 m a^{-1} over the 7-year period. Note the
formation of a large proglacial lake that has developed since 2010 (Photo: C R Stokes)