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Proxy-based 300-year High Arctic climate warming record from Svalbard

Luoto, Tomi P.

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1 **Abstract**

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3 We used fossil Chironomidae assemblages and the transfer function approach to reconstruct
4 summer air temperatures over the past 300 years from a High Arctic lake in Hornsund, Svalbard.
5 Our aims were to compare reconstructed summer temperatures with observed (last 100 years)
6 seasonal temperatures, to determine a potential climate warming breakpoint in the temperature
7 series and to assess the significance and rate of the climate warming trend at the study site. The
8 reconstructed temperatures were consistent with a previous proxy record from Svalbard and showed
9 good correlation with the meteorological observations from Bjørnøya and Longyearbyen. From the
10 current paleoclimate record, we found a significant climate warming threshold in the 1930s, after
11 which the temperatures rapidly increased. We also found that the climate warming trend was strong
12 and statistically significant. Compared to the reconstructed Little Ice Age temperatures in late 18th
13 century cooling culmination, the present day summer temperatures are >4 °C higher and the
14 temperature increase since the 1930s has been 0.5 °C per decade. These results highlight the
15 exceptionally rapid recent warming of southern Svalbard and add invaluable information on the
16 seasonality of High Arctic climate change and Arctic amplification.

17

18 *Keywords:* Arctic amplification; Chironomidae; Climate change; Paleoclimatology;
19 Paleolimnology; Temperature

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26 **Introduction**

27

28 Although the Arctic plays a globally significant role in the ongoing climate change, the long-term
29 climate patterns have been challenging to establish, especially in the High Arctic. The homogenized
30 Svalbard Airport (Longyearbyen) temperature record is one of the rare long-term instrumental
31 temperature series from the High Arctic (Nordli et al., 2010), but its early part (1912-1920) may be
32 less reliable due to series combination from different sources (Kohler et al., 2002). Because of
33 scarcity of long instrumental records from the High Arctic, proxy-based indirect reconstructions are
34 needed to interpret Arctic trends in terms of past long-term climate oscillations. This long-term
35 information is crucial for thorough understanding of natural climate dynamics and ongoing and
36 future trends in Arctic climate change from local to regional scales.

37 In addition to ice core records (Klein et al., 2016; Lecavalier et al., 2017), lake
38 sediment archives are the most useful proxy sources for paleotemperature reconstructions (Besonen
39 et al., 2008; Kaufman, 2009). From the variety of different lake sediment paleolimnological
40 temperature proxies, fossil chironomids (Insecta: Diptera: Chironomidae) have proven most useful
41 for reconstructions of Arctic climate change for several reasons (Thomas et al., 2008; Axford et al.,
42 2009; Nazarova et al., 2017). Most chironomids have aquatic larval stage, which leave behind well-
43 preserved chitinous head capsules (Hofmann, 1988). Since chironomids are regularly encountered
44 even in the coldest lakes and they are highly sensitive to temperature, with each taxa having a
45 specific temperature preference (Eggermont & Heiri, 2012; Engels et al., 2014), taxonomical
46 analysis of chironomid head capsules readily provides information on prevailing climate conditions
47 at each chronologically dated interval of a sediment downcore profile. By combining
48 biostratigraphical analysis with available chironomid-based temperature training sets (calibration-
49 in-space) it is possible to provide quantitative estimates of paleotemperature. In fact, chironomid-
50 based temperature models for the Arctic areas have become more available nowadays with a pan-

51 Arctic coverage (Self et al., 2011; Fortin et al., 2015; Nazarova et al., 2015). In this transfer
52 function approach, multivariate statistical models, such as those based on weighted-averaging and
53 partial least squares techniques, relate modern communities (surface sediment assemblages from
54 multiple lakes) to environmental conditions (e.g. temperature) that can be further applied to fossil
55 assemblages from deeper sediment layers and reconstructions of past environmental changes (Shala
56 et al., 2017; Pliik et al., 2019).

57 As the Arctic has a large influence on global climate system, the paleoclimate
58 reconstructions in the Arctic provide a basis to understand longer-term climate trends and to assess
59 the consequences of threshold changes in regional climate system and their dynamics. During the
60 recent decades, most profound warming in the Arctic, including Svalbard (Førland et al., 2011), has
61 taken place during winter. Moreover, paleoclimate evidence, which is strongly focused on summer
62 conditions, shows that Arctic summers are now warmer than at any time during at least the last
63 Millennium (Werner et al., 2018). It has also been shown that changes in the length of the ice-free
64 season have triggered a set of interlinked feedbacks that will amplify future rates of summer
65 warming (Chapin et al., 2005).

66 In this study, we use a fossil chironomid biostratigraphy and apply a regional
67 calibration model to quantitatively reconstruct mean July air temperatures from a 300-year-long
68 High Arctic lake sediment profile derived from Revvatnet in Hornsund, southern Svalbard. We test
69 the reconstructed values of the last 100 years against available meteorological data with special
70 interest on differences between summer and annual temperatures. The aims of the study include
71 determining a potential breakpoint for climate warming in southern Svalbard and to assess the
72 significance of possible climate warming trend. We also estimate the rate of climate warming in the
73 study area, which is of high significance since Svalbard is located in the climatically particularly
74 sensitive region at an intersection of Arctic and Atlantic oceanic water-masses where the Polar
75 Front develops (Isaksson et al., 2007; Majewski et al., 2009). Research carried out in the recent

decades show that in the European Arctic, the air temperature increase during the Medieval Warm Period (MWP) and Modern Warming (MW) correlate with the strong influence of the warm Atlantic Water (Wanamaker et al., 2012). In turn, the weakening of the Atlantic Meridional Overturning Circulation and lower heat transport to the Arctic might be responsible for the Little Ice Age (LIA) cooling (Lund et al., 2006). At present, the climate/oceanographic conditions in the west Spitsbergen fjords are shaped mainly by the inflow of warm and highly saline Atlantic waters transported from the south by West Spitsbergen Current (Nilsen et al., 2016). Therefore, considering the unique ocean-atmosphere interplay of the study area, disentangling detailed features of long-term development in the climate of southern Svalbard is invaluable to understand past, present and future large-scale Arctic climate processes, feedback mechanisms and land-ocean-atmosphere interactions.

87

88 **Material and methods**

89

90 **Study site**

91

Revvatnet (77.022°N, 15.368°E; 30 m a.s.l.) is an oligotrophic lake located near the Hornsund fjord, southern Svalbard (Fig. 1a). The lake has a surface area of 0.9 km² and a maximum depth of 26 m (Fig. 1b). The measured epilimnetic pH of the lake was 7.6 in June 2013. The average modern July air temperature is 4.8 °C (Cisek et al., 2017) with daily temperatures generally varying between 3 and 10 °C at the Hornsund meteorological station (Norwegian Meteorological Institute) located 4 km southeast from Revvatnet at the Polish Polar Station Hornsund. An approximately 2 °C increase in summer air temperature has been instrumentally observed since the initiation of measurements in 1979 (Marsz & Styszyńska, 2013). The catchment of Lake Revvatnet is characterized by periglacial tundra with outwash plains, ancient marine terraces, talus and proluvial cones, and undulating

101 ground moraine that appear all around the Hornsund Bay and on the hills of adjacent mountains
102 (Ojala et al., 2016). There are several side hanging valleys with active glaciers near Revvatnet, such
103 as Eimfjellbreane, Gangsbreen, and Skålfjellbreen, but no geomorphological evidence exists that
104 would suggests glaciers advancing and covering the entire Revvatnet basin during the Late
105 Holocene. However, the hydrology of the basin is governed by the discharge of surface runoff
106 waters via creeks into the basin from the north, which at least partly originates from valley glaciers.
107

108 **Sediment samples and chironomid analysis**

109
110 A 30-cm sediment profile RE2 sampled with a Kajak corer in June 2013 was used in the present
111 study. The core was taken from a water depth of 23.5 m (Fig. 1b) as part of a larger lake survey.
112 Further details on sampling can be found from a previous publication (Ojala et al., 2016). ^{137}Cs
113 analysis was used to indicate an age horizon for the atmospheric nuclear weapons testing maximum
114 fallout that occurred in 1963 CE (Fig. 2). The ^{137}Cs analysis was performed using an EGandG Ortec
115 ACE TM—2 K gamma spectrometer equipped with a four-inch NaI/Tl detector at the Geological
116 Survey of Finland. The age horizon of the RE2 core was verified by ^{137}Cs analysis of other cores
117 from the lake (RE1, RE3 and RE4).

118 Results of fossil chironomid community analysis are previously published in a
119 multiproxy paper focusing on long-term ecological shifts, biogeochemical cycling and microplastic
120 accumulation in Revvatnet (Luoto et al., 2019). In brief, standard methods were used for
121 chironomid analysis and a minimum head capsule counting sum per sample was set to 50 (Brooks
122 et al., 2007). The most common chironomid taxa (≥ 2 occurrences) are given in Fig. 3.

123

124 **Numerical methods**

125

126 For temperature reconstruction, we used a chironomid-based temperature training set constructed on
127 basis of several North Scandinavian datasets (Luoto, 2009; Luoto et al., 2014, 2016; Luoto & Ojala,
128 2017) and here further updated it with 10 additional High Arctic sites mostly from the Hornsund
129 area and Nordaustlandet. The mean July air temperature gradient of the model is 1.8-17.1 °C. As
130 the model type, locally weighted-weighted average (LWWA) regression with squared chi-squared
131 distance as the dissimilarity coefficient was used. LWWA is potentially suitable for detecting
132 environmental signal at the training set gradient ends, since it creates “local” datasets (cold lakes in
133 the current case), which have weighted input in the reconstruction. The number of samples in
134 “local” training set was set to 20 and the species data was log10 transformed. The model includes
135 191 sites and 132 taxa and has jackknife cross-validated coefficient of determination (R^2_{Jack}) of
136 0.91, root mean squared error of prediction (RMSEP) of 0.88 °C (5.8% of the training set
137 temperature gradient) and mean and maximum biases of 0.11 and 4.11 °C, respectively. Sample-
138 specific modeling errors (estimated standard error of prediction = eSEP) in the Revvatnet
139 reconstruction (including all taxa) were determined using bootstrapping cross-validation with 999
140 iterations.

141 For comparison with the present reconstruction, we used the temperature data (June to
142 August) published by D’Andrea et al. (2012), which is based on alkenone unsaturation in Lake
143 Kongressvatnet located ~100 km north from Revvatnet (Fig. 1a). The Kongressvatnet data were
144 obtained from the World Data Center for Paleoclimatology and NOAA’s National Climatic Data
145 Center, Paleoclimatology Branch website (<http://www.ncdc.noaa.gov/paleo/paleo.html>). In
146 addition, we compared the recent part (past ~100 years) with available meteorological data from the
147 Svalbard (Longyearbyen) airport (~140 km north from Revvatnet) and from Bjørnøya (~300 km
148 south from Revvatnet). The mean annual air temperature data from Longyearbyen and the mean
149 July air temperature data from Bjørnøya were available through the online database of the
150 Norwegian Meteorological Institute (<http://eklima.met.no/>). The early part (1912-1920) of the

151 Longyearbyen airport record was not used due to doubts on its reliability (Kohler et al., 2002). The
152 temporally adjusted (closest years matched) records were statistically compared using Pearson
153 correlation statistics.

154 Since the chironomid assemblage data had a linear (non-unimodal) response, the
155 community shifts were assessed using a principal component analysis (PCA) with the program
156 Canoco 5 (Šmilauer & Lepš, 2014). The PC1 scores were compared with site-specific temperatures
157 using Pearson Product-moment correlation coefficient (R), corrected coefficient of determination
158 (R^2_{adj}) and the level of statistical significance ($p < 0.05$) to verify that the communities were
159 responding to temperature. Using the modern analogue technique, the cut-level of the 2nd percentile
160 of all squared chi-squared distances in the modern calibration data was determined. These distances
161 were then compared to the distance between each fossil assemblage and its most similar assemblage
162 in the modern data set and used to define ‘close’ and ‘no close’ analogues. Fossil samples having
163 values below the 2nd percentile dissimilarity threshold were hence consider to have ‘close’
164 analogues in the calibration data, and consequently, ability to provide reliable temperature
165 estimates. Segmented regression analysis was used to identify statistically significant breakpoint in
166 the temperature reconstruction applying a minimum confidence level of 95%. The selection of the
167 best breakpoint and function type was based on maximizing the statistical coefficient of
168 explanation, and performing tests of significance using the program SegReg (Oosterbaan, 2005).

169 To assess statistically significant trends in the reconstruction, the Mann-Kendall trend
170 test (Gilbert, 1987) was used. In the non-parametric test for trend, the S -statistic is negative for a
171 negative trend, zero for no trend and positive for an increasing trend. For a trend to have statistical
172 significance, the p -value was required to be <0.05 . To further depict general trends and stabilize
173 chronological uncertainty and noise in the reconstructed values, LOESS smoother and the
174 LOWESS (LOcally WEighted Scatterplot Smoothing) (Cleveland, 1979, 1981) algorithm was
175 applied with a span 0.4. In illustrations of the breakpoint and trend analyses, temperature anomalies

176 standardized to the record mean were used to exclude potential error originating from the fact that
177 the study site locate close to the end of the training set temperature gradient (potential systematic
178 overestimation of temperatures).

179

180 **Results**

181

182 The ^{137}Cs analysis of different cores from Revvatnet, showed a parallel peak at ~5 cm for all three
183 cores (RE1-3) from the southern basin (Fig. 2). The onset of Cs fallout from nuclear weapons
184 testing in the early 1950s corresponds in RE2 for 6 cm (initial increase, assigned sample-specific
185 year 1953 CE according to linear age modeling) and the maximum fallout in 1963 CE for 5 cm
186 (maximum peak). A faster sedimentation rate was assigned for the northern basin (RE4), which
187 receives melt waters from the glacier and has turbid water column, consequently leading to higher
188 local sediment accumulation rate. Since the rate of sedimentation in the southern basin is
189 consistently of similar magnitude and the ^{137}Cs peak is very distinct, it can be expected that no
190 major and/or sudden changes in the rate of sediment deposition has occurred in this part of the
191 basin. Chronological extrapolation provides an age estimate of ~1720 CE for the bottom core, but
192 since the lower part of the sediment profile lacks chronological control, this estimate is uncertain.
193 The rate of sedimentation in the basin is generally increased towards the present day (with lower
194 rate of compaction), because of climate warming and increase in the catchment-derived material
195 (Ojala et al. 2016; Luoto et al. 2019), so if anything, the extrapolated ages are more likely older than
196 younger.

197 The Revvatnet RE2 sediment profile consisted of 14 taxa (Luoto et al., 2019), of
198 which 10 most common (≥ 2 occurrences) are shown in Fig. 3. All taxa were used in the temperature
199 reconstruction. The most abundant chironomids in Revvatnet were *Oliveridia tricornis* (abundant
200 between ~1720 and 1980 CE), *Micropsectra radialis*-type (1720-1820 CE and 1920 CE-present)

201 and *Hydrobaenus lugubris*-type (1780-1910 CE and 1960 CE-present). *Orthocladius trigonolabis*-
202 type, *O. consobrinus*-type and *Metriocnemus eurynotus*-type increased in the recent sediments.

203 The primary PC axis 1 scores for chironomids in the Revvatnet record showed little
204 changes (generally between -1 and 0 PCA units) from 1720 CE until values began to increase from
205 the 1940 CE onward (Fig. 4). The highest values were reached between 1980 CE and present (~2-3
206 PCA units). The secondary PC axis 2 had highest values (~1-2 PCA units) in the mid-stratigraphy
207 (1830-1900 CE) and lowest values between 1720 and 1780 CE and between 1920 and 1940 CE
208 (generally between -1 and -2 PCA units).

209 The chironomid-based mean July air temperature reconstruction resulted in values
210 varying between ~4 and 8 °C (Fig. 4). During the 18th century the temperatures remained at 4-5 °C.
211 Between 1820 and 1920 CE, the values were slightly higher varying between ~5 and 6 °C.
212 According to the reconstruction, a colder period (~4 °C) prevailed in the 1920s and 1930s. Since
213 then, the temperatures rapidly increased reaching 6 °C in the 1950s, 7 °C in the 1980s and 8 °C in
214 the 2000s. The inferred value for the surface sample is higher than the observed July average,
215 however, it is within the general modern July temperature variability of 3 to 10 °C at the Hornsund
216 station. The surface sample also has the highest sample-specific error, which is almost 2 °C, while
217 the other samples generally have errors below 1.5 °C (Fig. 4). All samples had good modern
218 analogues (2 percentile dissimilarity threshold 7.5 minDC), with the most similar communities in
219 the early and most recent parts of the profile (3-5 minDC) (Fig. 4).

220 The temperature reconstruction correlated significantly with chironomid primary PC
221 axis with R of 0.82, R^2_{adj} of 0.65 and $p < 0.001$. There was no significant correlation ($p = 0.145$)
222 between inferred temperature and the secondary PC axis. When comparing the temperature
223 reconstructions from Revvatnet and Kongressvatnet (Fig. 4), a significant correlation was found
224 with R of 0.56, R^2_{adj} of 0.29 and p of 0.001. Both records held a simultaneous initiation of
225 temperature increasing trend from the 1940s onward. Based on the segmented regression analysis, a

226 statistically significant ($p < 0.05$) optimal breakpoint in the Revvatnet temperature reconstruction
227 was found at 1932 CE. In the regression function, there was a horizontal segment followed by
228 sloping (Fig. 5). The Revvatnet mean July air temperature reconstruction also correlated with the
229 100-year observational mean annual air temperatures observed at the Longyearbyen airport ($R =$
230 0.77 , $R^2_{\text{adj}} = 0.56$ and p of 0.003) and the July temperatures observed in Bjørnøya ($R = 0.87$, $R^2_{\text{adj}} =$
231 0.74 and p of 0.001) (Fig. 6).

232 According to the Mann-Kendall trend test, there was a strong ($S = 233$, $Z = 4.1$) and
233 statistically significant ($p < 0.001$) increasing trend in the reconstructed values from Revvatnet (Fig.
234 7). Following this trend, the LOESS smoothed temperature anomalies (standardized to record mean)
235 turned from negative to positive values in the 1930s. The most negative temperature anomaly (-1.3
236 $^{\circ}\text{C}$) occurred in the beginning and the most positive (2.3 $^{\circ}\text{C}$) at the end of the sequence.

237

238 Discussion

239

240 Chironomid fauna of the Revvatnet sediment stratigraphy consisted of temperature sensitive taxa,
241 such as the cold indicating *Oliveridia tricornis*, which was the most abundant chironomid and
242 continuously present until the 1970s. Another cold-indicating chironomid in the calibration set,
243 *Micropsectra radialis*-type, thrived during periods 1720-1820 CE and 1920 CE-present. Warmer
244 indicating chironomids included *Orthocladius trigonolabis*-type, *O. consobrinus*-type and
245 *Metriocnemus eurynotus*-type, which increased from the 1970s onward (Fig. 3). Although the latter
246 taxa have been known to have preference for warmer lakes in northern Europe, they are also known
247 to be more common in bird-impacted nutrient-enriched lakes of Svalbard (Brooks & Birks, 2004;
248 Luoto et al., 2014, 2015). Therefore, this study cannot fully separate the climate signal from the
249 potential influence of increasing bird impact and nutrient enrichment in Revvatnet. However, the
250 size and volume of Revvatnet is considerable compared to bird-impacted strand flat ponds reported

251 by Brooks and Birks (2004) and Luoto et al. (2014, 2015), which is why the contribution of bird
252 guano is probably a less important factor explaining the changes. Also, to confront this problem we
253 compared the chironomid-inferred temperatures with observational temperature records
254 (meteorological validation of the reconstruction) in the more recent time interval when also these
255 chironomid taxa that potentially favor bird impacted lakes appeared in the record.

256 Since the chironomid primary PC axis correlated strongly and significantly with the
257 chironomid-based temperature reconstruction and there was no significant correlation with the
258 secondary PC axis and inferred temperatures, the data suggests that chironomid assemblages in the
259 Revvatnet sequence were responding to the reconstructed environmental variable (cf. de Jong et al.,
260 2013). As all the fossil assemblages also had good modern analogues in the temperature calibration
261 set (Fig. 4), we were subsequently able to “reliably” reconstruct past summer temperature
262 variability from the Revvatnet core using chironomids. Compared to the temperature reconstruction
263 from Kongressvatnet in western Svalbard (D’Andrea et al., 2012), a similar trend was found (Fig.
264 4). Although these two proxy-based reconstructions had statistically significant correlation, they
265 also exhibited differences, which however, may be partly owing to the inaccuracy rising from the
266 extrapolated lower part (below 7 cm/prior 1950s) of the Revvatnet record. Nonetheless, mismatch
267 in ages would likely worsen the correlation between the two records rather than improve it.

268 The warmer temperatures within the LIA at Kongressvatnet between 1740-1770 CE
269 were not as clearly present in the chironomid-based reconstruction at Revvatnet. Although it has
270 been shown from elsewhere in Scandinavia that the LIA was not uniformly cold but often separated
271 in two cold phases (Zawiska et al., 2017), it is also clear that it had marked spatial variability in
272 timing and magnitude even between relatively adjacent sites (Tiljander et al., 2003; Rantala et al.,
273 2016; Luoto et al., 2017a). Even today, the temperature varies considerably across the Svalbard
274 High Arctic archipelago having an influence on permafrost and glacier activity (e.g. Humlum et al.,
275 2003; Marsz & Styszyńska, 2013). Martín-Moreno et al. (2017), for example, concluded that the

276 influence of the LIA climate on glaciers was dissimilar in different parts of Svalbard depending on
277 local climate but also glacier dynamics and surging. Pawłowska et al. (2016) revealed a sharp
278 change in the sea-environmental conditions in central Hornsund at ~1800 CE and their study on the
279 ancient foraminiferal DNA (aDNA) revealed that the transition to the LIA between 1600 and 1800
280 CE was well marked by the increase in the percentage of monothalamous foraminifera aDNA
281 sequences (mainly from genus *Bathysiphon*) and additionally by low sediment accumulation rate
282 and low ice rafted debris (IRD) flux. This provided that the position of the glacier fronts was
283 relatively distant to the fjord center, however, the fjord was influenced by the Arctic waters and
284 melt waters (Pawłowska et al., 2016). Hence, the differences between lacustrine and marine records
285 may result from the direct contact of fjord waters with developed tidal glaciers fronts.

286 Furthermore, the alkenone-based reconstruction from Kongressvatnet did not show as
287 distinct temperature rise from the 1940s onward as the current chironomid-based reconstruction
288 from Revvatnet. Curiously, the largest sample-specific errors in the chironomid-based
289 reconstruction are in the more recent samples (Fig. 4) that could imply more uncertain temperature
290 estimations. Nonetheless, there are close modern analogues in the training set for the samples in the
291 later part of the core suggesting that the reconstruction does not become less reliable. As the best
292 way to determine reliability of a temperature reconstruction is to compare the inferred values
293 against instrumentally observed values over the observational period (Larocque-Tobler et al., 2015),
294 we tested the Revvatnet reconstruction against available mean July meteorological temperatures
295 from Bjørnøya and annual meteorological temperatures from Longyearbyen (Fig. 6). In addition to
296 statistically significant correlation between the Revvatnet temperatures and the observational
297 records, we also found that the summer time records were similar in their magnitude of recent
298 change suggesting that the current reconstruction is reliable also in the most recent sediment
299 section.

300 Similar to the hydroclimatic appearance of the LIA (Helama et al., 2017; Linderholm
301 et al., 2018), there is distinct spatial variability in the onset of the MW in northern Scandinavia
302 (Weckström et al., 2006; Matskovsky & Helama, 2014; Luoto & Nevalainen, 2017). The segmented
303 regression analysis of the Revvatnet reconstruction showed a horizontal segment followed by
304 sloping with the statistically significant breakpoint at 1932 CE (Fig. 5), hence indicating that a
305 climate warming threshold occurred in the 1930s. A similar climate warming development of the
306 past century has been meteorologically observed from Bjørnøya, 300 km south of Revvatnet (Fig.
307 6). Similarly between the inferred and observed mean July air temperature records, the temperatures
308 rapidly increased in the 1930s and 1940s but stabilized to only a slight warming from the 1950s
309 until a new distinct temperature increase during the most recent decades. The annual mean air
310 temperature observations from Longyearbyen airport, 140 km north of Lake Revvatnet, show partly
311 differing story with temperatures remaining constantly low during the past century until a slow
312 progressive increase in the 1960s followed by rapidly increasing trend during the most recent
313 decades, which is similar to the Revvatnet and Bjørnøya summer temperature records (Fig. 6). The
314 differences between mean July and mean annual temperature records suggest significant variability
315 between seasonal temperature trends in Svalbard. In previous paleoclimatic studies from Lake
316 Svartvatnet, located 15 km south of Lake Revvatnet, it has been shown that in centennial-scale
317 chironomid-based mean July air temperature and stable oxygen isotope-based mean annual air
318 temperature reconstructions the general trends are similar but significant differences occur in the
319 magnitude of climate changes (Arppe et al., 2017; Luoto et al., 2018). These studies, however, were
320 conducted with significantly lower resolution for the last centennial than in the present study, but
321 for example, the late Holocene cooling trend (cf. Wanner et al., 2008) was less pronounced in the
322 annual record, while the annual record demonstrated a much more prominent LIA signal together
323 with emphasized MW compared to the summer temperature record. Therefore, the present findings
324 well agree with the previous evidence on that summer and annual temperature trends have similar

325 general trends, but also significant differences in magnitude and timing, highlighting the
326 significance of seasonal climatic components in the High Arctic.

327 According to meteorological observations in Hornsund, the summer air temperatures
328 have increased 2 °C since the beginning of instrumental measurements in 1979 (Marsz &
329 Styszyńska, 2013). This agrees well with our present reconstruction, which shows an increase from
330 6.3 °C in the mid-1970s to the present 8.3 °C (Fig. 4). The ~2 °C rise also concurs with the
331 Bjørnøya observational record of mean July air temperatures, whereas in the observed annual
332 temperatures from Longyearbyen there is an over 3 °C temperature increase since the 1980s.
333 Therefore, it appears clear that winter warming is even greater than summertime warming in
334 Svalbard. For Svalbard, climate projections also suggest greater temperature increase in the future
335 during winter than summer (Førland et al., 2011).

336 A paleoclimate synthesis of Arctic-wide mean summer temperatures have shown that
337 the Arctic cooling trend, which was culminated during the LIA, was reversed during the 20th
338 century, with warmest decades occurring between 1950 and 2000 CE (Kaufman et al. 2009). The
339 present results from Revvatnet are in agreement with these pan-Arctic temperature anomalies (Fig.
340 7). The current sediment record extends back in time to the early 18th century, when the LIA was
341 still at its coldest in northern Europe (Osborn & Briffa, 2006; Zawiska et al., 2017). Compared to
342 the modern temperature inferred from the topmost sediment sample, the coldest temperatures
343 inferred in the 18th century were 4.3 °C lower (Fig. 7). This difference between the present and LIA
344 temperatures is hence considerably larger than the 2 °C difference estimated from boreal northern
345 Europe (Luoto, 2013) but at similar magnitude as in the north-eastern European Russian Arctic (5
346 °C) (Luoto et al. 2017b), underlining the influence of Arctic climate amplification. Our data shows
347 a statistically significant temperature increasing trend from the LIA towards the present with more
348 stable 100-year period between ~1820 and 1920 CE (Fig. 7), probably reflecting the time phase
349 between the LIA and the MW that was characterized by reduced variability in the North Atlantic

Oscillation index (Trouet et al., 2009; Luoto & Nevalainen, 2018). According to the breakpoint analysis (Fig. 6) and LOESS trend (Fig. 7), a climate warming threshold in the 1930s was assigned. The temperature increase from the 1720 to 1820 CE was relatively rapid, approximately 0.2 °C per decade, but the temperature increase from the 1930s until present clearly exceeds this being approximately 0.5 °C per decade (Fig. 7). Previously, the temperature increase from the 1960s to 2050 CE has been projected to be 0.3 °C per decade (Hanssen-Bauer, 2002), which is slightly lower than suggested for the period from 1960 CE to present day by the current reconstruction. In these temperature comparisons it should be noted though that the used temperature calibration model has an RMSEP of 0.88 °C and the sample-specific errors vary between 1.1 and 2.0 °C. While these uncertainties are seemingly large compared to the late Holocene climate oscillations, it is likely that potential errors deriving from the chironomid-based temperature estimates are systematic between the focal samples throughout the profile considering that temperature is the dominant community forcer and secondary environmental factors do not play a significant role (Heiri et al. 2003; Brooks 2006). Moreover, the RMSEP of the model used in this study is much lower than reported from other existing chironomid-based temperature transfer functions, such as the widely used Swiss, Norwegian and their combined version with RMSEPs of 1.3-2.6 °C (Heiri et al., 2011). Therefore, the results of this study well manifests the exceptional speed and scale of the ongoing climate warming in southern Svalbard and provides an important perspective for estimations of the present and future Arctic environmental change.

369

370 **Conclusions**

371

The present 300-year-long reconstruction of mean July air temperature from Revvatnet showed significant correlation with a previous paleolimnological reconstruction from Kongressvatnet, ~100 km north from our study site, however, with more distinct recent warming. The Revvatnet

375 paleotemperature record also correlated significantly with the meteorological mean July
376 temperatures from Bjørnøya over the observational period (100 years) showing close
377 correspondence. Compared to instrumental temperatures from Svalbard Airport (~140 km north),
378 the initiation of rapidly increased temperatures occurred earlier in the summer temperature records
379 than in the annual temperature record. According to the breakpoint analysis, a climate warming
380 threshold occurred in the summer temperatures in the 1930s. We also found that the climate
381 warming trend was progressive and statistically significant. Since the LIA, the summer
382 temperatures have increased by $>4^{\circ}\text{C}$ being far greater warming than in continental Scandinavia.
383 Following the breakpoint in temperature increase in the 1930s, the warming rate has been as much
384 as 0.5°C per decade. These findings hence emphasize the influence of Arctic amplification and
385 significance of seasonal climate components and suggest climate warming that is exceptional in its
386 magnitude. The scale of temperature change over the past century proposes cascading
387 environmental impacts in this climatically ultrasensitive region, where significant environmental
388 and ecological shifts have already been observed.

389

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391

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670 **Tables**

671

672 Table 1. Characteristics of the used chironomid-based calibration set consisting of boreal, subarctic
673 and Arctic lakes.

Mean July air temperature gradient (°C)	15.3 °C (17.1-1.8°C)
Total number of sites	191
Barren tundra sites	42
Mountain birch woodland sites	47
Pine and birch forest sites	38
Spruce, pine, and birch forest sites	64
Number of taxa	132
Calibration technique	Locally weighted-weighted averaging (LWWA)
Number of samples in “local” training set	20
Coefficient of determination (R^2_{Jack})	0.91
Root mean squared error of prediction, RMSEP	0.88 °C
Mean modeling bias	0.11 °C (0.00-4.11 °C)

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683 **Figure captions**

684

685 **Fig. 1** Location of the study site Revvatnet in southwestern Svalbard (a) together with lake
686 bathymetry (b).

687

688 **Fig. 2** ^{137}Cs activity in the sediment cores RE1-4. The ^{137}Cs peak refers to the nuclear weapons
689 testing maximum fallout in 1963 CE. Core RE2 was used in the chironomid analysis.

690

691 **Fig. 3** Chironomid biostratigraphy of the 10 most common taxa (≥ 2 occurrences) from Revvatnet
692 (Svalbard). The assemblage compositions are expressed as relative abundance of total chironomids.
693 Full chironomid assemblage composition is published elsewhere (Luoto et al., 2019). Also the rare
694 taxa missing from the figure were included in the temperature reconstruction.

695

696 **Fig. 4** Principal component analysis (PCA) axis scores for chironomids, chironomid-based mean
697 July air temperature reconstruction, sample-specific prediction errors estimated using bootstrapping
698 cross-validation and closest modern analogues in the sediment record from Revvatnet, southwestern
699 Svalbard. Also shown are the alkenone-based temperature reconstruction from Kongressvatnet,
700 western Svalbard (D'Andrea et al., 2012), the model's prediction error (root mean squared error of
701 prediction, RMSEP) and the 2 percentile modern analogue dissimilarity threshold.

702

703 **Fig. 5** Optimal breakpoint at 1932 CE in the chironomid-inferred temperature reconstruction (gray
704 dots) from Revvatnet (Svalbard) assessed using segmented regression analysis. Shown are the 95%
705 confidence block of the optimal breakpoint and the 95% confidence belt.

706

707 **Fig. 6** Chironomid-inferred mean July air temperature reconstruction (blue) with sample-specific
708 errors from Revvatnet (Svalbard) compared with mean annual meteorological observations (red)
709 from Svalbard Airport (Longyearbyen) and mean July air temperature observations (green) from
710 Bjørnøya over the instrumental period (past ~100 years).

711

712 **Fig. 7** Reconstructed summer temperature anomalies (white dots) from the Revvatnet (western
713 Svalbard) sediment record using fossil chironomids and the transfer function approach. According
714 to the Mann-Kendall trend test, there is a statistically significant increasing trend in the samples. To
715 stabilize chronological uncertainty and noise in the reconstructed values, a LOESS smooth was used
716 (blue/red curve). Also shown are the sample-specific errors (eSEP) estimated using bootstrapping
717 cross-validation (dashed lines).