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# Post-1980 shifts in the sensitivity of boreal tree growth to North Atlantic Ocean dynamics and seasonal climate

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1 **Post-1980 shifts in the sensitivity of boreal tree growth to North Atlantic Ocean**  
2 **dynamics and seasonal climate**

3

4 Tree growth responses to North Atlantic Ocean dynamics

5

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25

26 **Highlights**

- 27
- 28 • A significant boreal tree growth response to oceanic and atmospheric indices emerged  
29 during the 1980s.
  - 30 • This was particularly observed in western and central boreal Quebec and in central and  
31 northern boreal Sweden.
  - 32 • The post-1980 sensitivity to large-scale indices synchronized with changes in tree  
33 growth responses to local climate.
  - 34 • Future large-scale dynamics may impact forest growth and carbon sequestration to a  
35 greater extent than previously thought.

36 **Abstract**

37 The mid-20<sup>th</sup> century changes in North Atlantic Ocean dynamics, e.g. slow-down of the  
38 Atlantic meridional overturning thermohaline circulation (AMOC), have been considered as  
39 early signs of tipping points in the Earth climate system. We hypothesized that these changes  
40 have significantly altered boreal forest growth dynamics in northeastern North America (NA)  
41 and northern Europe (NE), two areas geographically adjacent to the North Atlantic Ocean. To  
42 test our hypothesis, we investigated tree growth responses to seasonal large-scale oceanic and  
43 atmospheric indices (the AMOC, North Atlantic Oscillation (NAO), and Arctic Oscillation  
44 (AO)) and climate (temperature and precipitation) from 1950 onwards, both at the regional  
45 and local levels. We developed a network of 6,876 black spruce (NA) and 14,437 Norway  
46 spruce (NE) tree-ring width series, extracted from forest inventory databases. Analyses  
47 revealed post-1980 shifts from insignificant to significant tree growth responses to summer  
48 oceanic and atmospheric dynamics both in NA (negative responses to NAO and AO indices)  
49 and NE (positive response to NAO and AMOC indices). The strength and sign of these  
50 responses varied, however, through space with stronger responses in western and central  
51 boreal Quebec and in central and northern boreal Sweden, and across scales with stronger  
52 responses at the regional level than at the local level. Emerging post-1980 associations with  
53 North Atlantic Ocean dynamics synchronized with stronger tree growth responses to local  
54 seasonal climate, particularly to winter temperatures. Our results suggest that ongoing and  
55 future anomalies in oceanic and atmospheric dynamics may impact forest growth and carbon  
56 sequestration to a greater extent than previously thought. Cross-scale differences in responses  
57 to North Atlantic Ocean dynamics highlight complex interplays in the effects of local climate  
58 and ocean-atmosphere dynamics on tree growth processes and advocate for the use of  
59 different spatial scales in climate-growth research to better understand factors controlling tree  
60 growth.

61 **Keywords**

62 Climate change, Dendrochronology, Climate-growth interactions, Response functions,  
63 Teleconnections, Arctic amplification.

64

65 **1 Introduction**

66 Terrestrial biomes on both sides of the North Atlantic Ocean are strongly influenced by Arctic  
67 and Atlantic oceanic and atmospheric dynamics (D'Arrigo *et al.*, 1993; Ottersen *et al.*, 2001;  
68 Girardin *et al.*, 2014). Some mid-20<sup>th</sup> century changes in the dynamics of the North Atlantic  
69 Ocean have been considered as early signs of tipping points in the Earth climate system  
70 (Lenton *et al.*, 2008; Lenton, 2011). The Atlantic Meridional Overturning Circulation  
71 (AMOC) exhibited an exceptional slow-down in the 1970s (Rahmstorf *et al.*, 2015). The  
72 cause of this slow-down is still under debate, but possible explanations include the weakening  
73 of the vertical structure of surface waters through the discharge of low-salinity fresh water  
74 into the North Atlantic Ocean, due to the disintegration of the Greenland ice sheet and the  
75 melting of Canadian Arctic glaciers. A further weakening of the AMOC may possibly lead to  
76 a wide-spread cooling and decrease in precipitation in the North Atlantic region (Sgubin *et al.*  
77 *et al.*, 2017), subsequently lowering the productivity of land vegetation both over northeastern  
78 North America and northern Europe (Zickfeld *et al.*, 2008; Jackson *et al.*, 2015). Despite  
79 increasing research efforts in monitoring climate-change impacts on ecosystems, effects of  
80 late 20<sup>th</sup> century changes in North Atlantic Ocean dynamics on mid- to high-latitude terrestrial  
81 ecosystems remain poorly understood.

82         The dynamics of North Atlantic oceanic and atmospheric circulation, as measured  
83 through the AMOC, North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices,  
84 strongly influence climate variability in northeastern North America (NA) and northern  
85 Europe (NE) (Hurrell, 1995; Baldwin & Dunkerton, 1999; Wettstein & Mearns, 2002). NAO  
86 and AO indices integrate differences in sea-level pressure between the Iceland Low and the

87 Azores High (Walker, 1924), with high indices representative of increased west-east air  
88 circulation over the North Atlantic. Variability in AMOC, NAO and AO indices affects  
89 climate dynamics, both in terms of temperatures and precipitation regimes. Periods of high  
90 winter NAO and AO indices are associated with below-average temperatures and more sea  
91 ice in NA and a warmer- and wetter-than-average climate in NE. Periods of low winter NAO  
92 and AO indices are, in turn, associated with above-average temperatures and less sea ice in  
93 NA and a colder- and dryer-than-average climate in NE (Wallace & Gutzler, 1981; Chen &  
94 Hellström, 1999). Low AMOC indices induce a wide-spread cooling and decrease of  
95 precipitation across the high latitudes of the North Atlantic region (Jackson *et al.*, 2015).

96 Boreal forests cover most of mid- and high-latitude terrestrial regions of NA and NE  
97 and play an important role in terrestrial carbon sequestration and land-atmosphere energy  
98 exchange (Betts, 2000; Bala *et al.*, 2007; de Wit *et al.*, 2014). Boreal forests are sensitive to  
99 climate change (Gauthier *et al.*, 2015). Despite general warming and lengthening of the  
100 growing season at mid- and high-latitudes (Karlsen *et al.*, 2009; IPCC, 2014), tree growth in  
101 many boreal regions lost its positive response to rising temperatures during the late-20<sup>th</sup>  
102 century (Briffa *et al.*, 1998). An increasing dependence on soil moisture in the face of the  
103 rapid rise in summer temperatures may counterbalance potential positive effects on boreal  
104 forest growth of increased atmospheric CO<sub>2</sub> concentrations (Girardin *et al.*, 2016). During the  
105 late 20<sup>th</sup> century, large-scale growth declines (Girardin *et al.*, 2014) and more frequent low  
106 growth anomalies (Ols *et al.*, 2016)- in comparison with the early 20<sup>th</sup> century- have been  
107 reported for pristine boreal spruce forests of NA. In coastal NE, climatic changes over the 20<sup>th</sup>  
108 century have triggered shifts from negative significant to non-significant spruce responses to  
109 winter precipitation (Solberg *et al.*, 2002). Annual variability in boreal forest tree growth  
110 patterns have shown sensitivity to sea ice conditions (Girardin *et al.*, 2014; Drobyshev *et al.*,  
111 2016) and variability in SSTs (Lindholm *et al.*, 2001). All changes in boreal tree growth

112 patterns and climate-growth interactions listed above may be driven by the dynamics of the  
113 North Atlantic Ocean. Understanding current and projected future impacts of North Atlantic  
114 Ocean dynamics on boreal forest ecosystems and their carbon sequestration capacity calls for  
115 a deeper spatiotemporal analysis of tree growth sensitivity to large-scale oceanic and  
116 atmospheric dynamics.

117         The present study investigates tree growth responses to changes in North Atlantic  
118 Ocean dynamics of two widely distributed tree species in the boreal forests of northeastern  
119 North America (black spruce) and northern Europe (Norway spruce). We investigated tree-  
120 growth sensitivity to seasonal large-scale indices (AMOC, NAO; AO) and seasonal climate  
121 (temperature and precipitation) over the second half of the 20<sup>th</sup> century. We hypothesize that  
122 shifts in tree growth sensitivity to large-scale indices and local climate are linked to major  
123 changes in North Atlantic Ocean dynamics. This study aims to answer two questions: (i) has  
124 boreal tree growth shown sensitivity to North-Atlantic Ocean dynamics? and (ii) does tree  
125 growth sensitivity to such dynamics vary through space and time, both within and across NA  
126 and NE?

127

## 128 **2 Material and methods**

### 129 **2.1 Study areas**

130 We studied two boreal forest dominated areas under the influence of large-scale atmospheric  
131 circulation patterns originating in the North Atlantic: the northern boreal biome of the  
132 Canadian province of Quebec (50°N-52°N, 58°W-82°W) in NA and the boreal biome of  
133 Sweden (59°N-68°N, 12°E-24°E) in NE (Fig. 1a). The selection of the study areas was based  
134 on the availability of accurate annually-resolved tree growth measurements acquired from  
135 forest inventories.

136         In northern boreal Quebec, mean annual temperature increases from north to south (-5

137 to 0.8 °C) and total annual precipitation increases from west to east (550 to 1300 mm), mainly  
138 due to winter moisture advection from the North Atlantic Ocean (Gerardin & McKenney,  
139 2001). In boreal Sweden, annual mean temperature increases from north to south (-2 to 6 °C)  
140 and annual total precipitation decreases from west to east (900 to 500 mm), mostly because of  
141 winter moisture advection from the North Atlantic Ocean that condenses and precipitates over  
142 the Scandinavian mountains in the west (Sveriges meteorologiska och hydrologiska institut  
143 (SMHI), 2016).

144 The topography in northern boreal Quebec reveals a gradient from low plains in the  
145 west (200-350 m above sea level [a.s.l.]) to hills in the east (400-800 m a.s.l.). In boreal  
146 Sweden, the topography varies from high mountains (1500-2000 m a.s.l.) in the west to low  
147 lands (50-200 m a.s.l.) in the east along the Baltic Sea. However, mountainous coniferous  
148 forests are only found up to ca. 400 m a.s.l. in the north (68°N) and ca. 800 m a.s.l. in the  
149 south (61°N).

150

## 151 **2.2 Tree growth data**

152 We studied tree growth patterns of the most common and widely distributed spruce species in  
153 each study area: black spruce (*Picea mariana* (Mill.) Britton) in Quebec and Norway spruce  
154 (*P. abies* (L.) H. Karst) in Sweden. A total of 6,876 and 14,438 tree-ring width series were  
155 retrieved from the Quebec (Ministère des Ressources naturelles du Québec, 2014) and  
156 Swedish forest inventory database (Riksskogstaxeringen, 2016), respectively. We adapted  
157 data selection procedures to each database to provide as high local coherence in growth  
158 patterns as possible.

159 For Quebec, core series were collected from dominant trees on permanent plots (three  
160 trees per plot, four cores per tree) between 2007 and 2014. Permanent plots were situated in  
161 unmanaged old-growth black spruce forests north of the northern limit for timber exploitation.

162 Core series were aggregated into individual tree series using a robust bi-weighted mean  
163 (robust average unaffected by outliers, Affymetrix 2002). To enhance growth coherence at the  
164 local level, we further selected tree series presenting strong correlation ( $r > 0.4$ ) with their  
165 respective local landscape unit master chronology. This master chronology corresponds to the  
166 average of all other tree series within the same landscape unit (landscape units are 6341 km<sup>2</sup>  
167 on average and delimit a territory characterized by specific bioclimatic and physiographic  
168 factors (Robitaille & Saucier, 1998)). This resulted in the selection of 790 tree series that were  
169 averaged at the plot level using a robust bi-weighted mean. The obtained 444 plot  
170 chronologies had a common period of 1885-2006 (Table 1). Plot chronologies were detrended  
171 using a log transformation and a 32-year spline de-trending, and pre-whitened using  
172 autocorrelation removal (Cook & Peters, 1981). Detrending aims at removing the low-  
173 frequency age-linked variability in tree-ring series (decreasing tree-ring width with increasing  
174 age) while keeping most of the high-frequency variability (mainly linked to climate). Pre-  
175 whitening removes all but the high frequency variation in the series by fitting an  
176 autoregressive model to the detrended series. The order of the auto-regressive model was  
177 selected by Akaike Information Criterion (Akaike 1974).

178 For Sweden, core series were collected within the boreal zone of the country (59°N-  
179 68°N) on temporary plots between 1983 and 2010. Temporary plots were situated in  
180 productive forests, i.e. those with an annual timber production of at least 1m<sup>3</sup>/ha. These  
181 forests encompass protected, semi-natural and managed forests. In each plot, one to three  
182 trees were sampled, with two cores per tree. Swedish inventory procedures do not include any  
183 visual and statistical cross-dating of core series at the plot level. To filter out misdated series,  
184 we aggregated core series into 4067 plot chronologies using a robust bi-weighted mean, and  
185 compared them to Norway spruce reference chronologies from the International Tree-Ring  
186 Data Base (International Tree Ring Data Bank (ITRDB), 2016). In total, seven ITRDB



187 reference chronologies were selected (Fig. 1b), all representative of tree growth at mesic sites  
 188 in boreal Sweden. Plot and reference chronologies were detrended and pre-whitened using the  
 189 same standard procedures used for the Quebec data. Each plot chronology was then compared  
 190 with its geographically nearest reference chronology - determined based on Euclidean  
 191 distance - using Student's t-test analysis (Student 1908). Plot chronologies with a t-test value  
 192 lower than 2.5 with their respective nearest reference chronology were removed from further  
 193 analyses (the t-test value threshold was set up according to the mean length of plot  
 194 chronologies (Table 1)). A total of 1256 plot chronologies (with a common period of 1936-  
 195 1995) passed this quality test (Table 1).

196

197 **Table 1.** Characteristics of tree-ring width chronologies\*.

	Quebec	Sweden 198
<b>Plot chronologies</b>		
Number	444	1256
Mean length (SD) [yrs.]	191 (59)	80 (3)
<b>Grid cell chronologies</b>		
Number	36	56
Plot chronologies per grid cell (SD)	12 (8)	23 (13)
Mean length (SD) [yrs.]	230 (47)	81 (13)
Common period	1885-2006	1936-1995
<b>Regional chronologies</b>		
Number	3	3
Grid cell chronologies per cluster	7/10/19*	14/19/23**
Length [yrs.]	212/196/263*	81/81/79**
Common period	1812-2008	1929-2008

199 \*Data for Q\_W, Q\_C and Q\_E chronologies respectively.

200 \*\*Data for S\_S, S\_C and S\_N chronologies respectively.

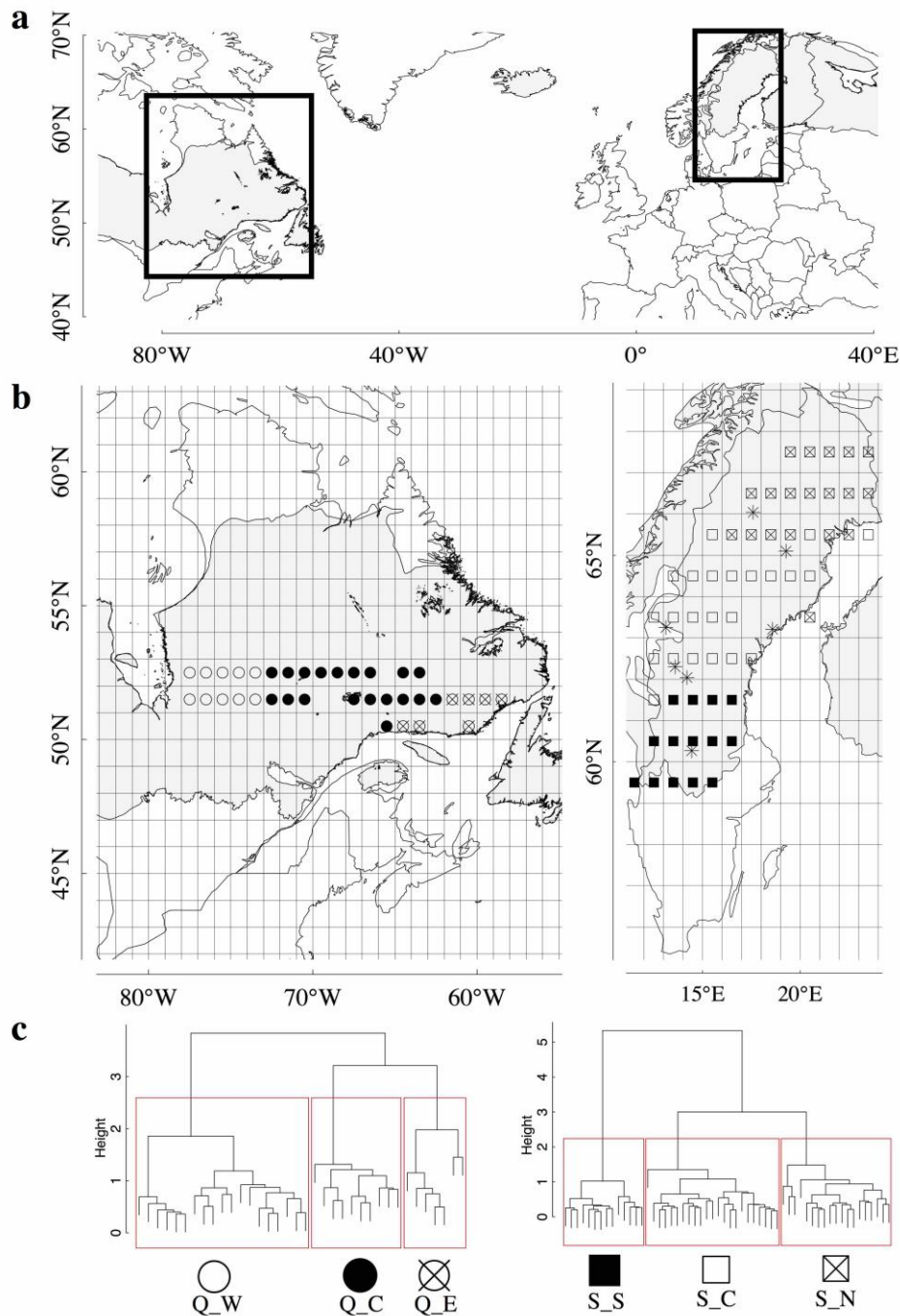
201

### 202 **2.3 Spatial aggregation of plot chronologies into regional chronologies in each study area**

203 Quality checked chronologies at the plot level were aggregated into 1° x 1° latitude-longitude  
 204 grid cell chronologies within each study area (Fig. 1b). Grid cell chronologies were calculated  
 205 as the robust bi-weighted mean of all plot chronologies within each grid cell. Grid cells

206 containing less than three plot chronologies were removed from further analyses. This  
207 resulted in a total of 36 and 56 grid cell chronologies in Quebec and Sweden, respectively  
208 (Fig. 1b, Table 1). Grid cells contained on average 12 and 23 plot chronologies in Quebec and  
209 Sweden, respectively (Table 1).

210 To investigate the influence of spatial scale in climate-growth sensitivity analyses, we  
211 performed an ordination of grid cell chronologies within each study area over their common  
212 period (Fig. 1c). The common period between grid cell chronologies was 1885-2006 and  
213 1936-1995 in Quebec and Sweden, respectively. Ordination analyses were performed in R  
214 using Euclidean dissimilarities matrices (*dist* function) and Ward agglomeration (*hclust*  
215 function) methods. Three main clusters were identified in each study area (Fig. 1c). Spatial  
216 extents of all clusters were consistent with well-defined bioclimatic regions, providing  
217 support to data selection procedures. In Quebec, clusters identified in the West (Q\_W) and the  
218 East (Q\_E) corresponded well to the drier and wetter northern boreal region, respectively  
219 (Fig. 1b & c). In Sweden, the cluster identified in the South (S\_S) corresponded to a  
220 combination of the nemo-boreal and southern boreal zones (Moen, 1999). The Swedish  
221 central (S\_C) and northern (S\_N) clusters corresponded to the mid-boreal and northern boreal  
222 zones, respectively (Fig. 1b & c) (Moen, 1999). Regional chronologies were built as the  
223 average of all grid cell chronologies within a cluster. In Sweden, inter-cluster correlations  
224 were all significant and ranged from 0.77 (S\_S vs S\_N) to 0.94 (S\_C vs S\_N). In Quebec,  
225 inter-cluster correlations were all significant and ranged from 0.44 (Q\_W vs Q\_E) to 0.52  
226 (Q\_C vs Q\_E) (see Appendix S1-S3 in Supporting Information). Henceforward, the terms  
227 'local level' and 'regional level' refer to analyses focusing on the grid cell chronologies and  
228 the six regional chronologies, respectively.



229

230 **Fig. 1** a: Location of the two study areas (black frame); b & c: Clusters identified in each  
 231 study area by ordination of  $1^\circ \times 1^\circ$  latitude-longitude grid cell chronologies. Ordination  
 232 analyses were performed over the common period between grid cell chronologies in each  
 233 study area using Euclidean dissimilarities matrices and Ward agglomeration methods. The  
 234 common period was 1885-2006 for Quebec and 1936-1995 for Sweden. Ordinations included  
 235 36 and 56 grid cell chronologies in Quebec and Sweden, respectively. A western (Q\_W),  
 236 central (Q\_C) and eastern (Q\_E) cluster were identified in Quebec and a southern (S\_S),  
 237 central (S\_C) and northern (S\_N) cluster were identified in Sweden. Reference chronologies

238 from the ITRDB used for the cross-dating of plot chronologies in Sweden are indicated with a  
239 \* (swed011, swed012, swed013, swed014, swed015, swed017 and swed312). The grey  
240 shading indicates the boreal zone delimitation according to Brant *et al.* (2013).

241

## 242 **2.4 Climate data**

243 For each grid cell, we extracted local seasonal mean temperature and total precipitation data  
244 (1950-2008) from the CRU TS 3.24 1° x 1°(Harris *et al.*, 2014), with seasons spanning from  
245 the previous (pJJA) through the current summer (JJA). Climate data were further aggregated  
246 at the regional level as the robust bi-weighted mean of climate data of all grid cells contained  
247 in each regional cluster (Fig. 1b & c). Seasonal AMOC indices (1961-2005, first AMOC  
248 measurements in 1961) were extracted from the European Center for Medium-Range Weather  
249 Forecast (Ocean Reanalysis System ORA-S3). Seasonal AO and NAO indices (1950-2008)  
250 were extracted from the Climate Prediction Center database (NOAA, 2016). Seasonal AMOC,  
251 NAO, and AO indices included previous summer, winter (DJF), and current summer. All  
252 seasonal climate data were downloaded using the KNMI Climate Explorer (Trouet & Van  
253 Oldenborgh, 2013) and were detrended using linear regression and thereafter pre-whitened  
254 (autocorrelation of order 1 removed from time series).

255

## 256 **2.5 Links between seasonal climate and growth patterns**

257 Analyses were run over the 1950-2008 period (the longest common period between tree  
258 growth and climate data), except with AMOC indices which were only available for 1961-  
259 2005. Tree growth patterns were correlated with seasonal climate variables (previous-to-  
260 current summer temperature averages and precipitation sums) and seasonal indices (previous  
261 summer, winter, and current summer AMOC, NAO, and AO) at the regional and local levels.  
262 To minimize type I errors, each correlation analysis was tested for 95% confidence intervals  
263 using 1000 bootstrap samples. In addition, moving correlation analyses (21-yr windows

264 moved one year at a time) were performed at the regional level using the same procedures as  
265 above. All calculations were performed using the R package *treeclim* (Zang & Biondi, 2015).  
266 For more details regarding bootstrapping procedures please see the description of the “*dcc*”  
267 function of this package.

268

## 269 **3 Results**

### 270 **3.1 Tree growth responses to seasonal climate**

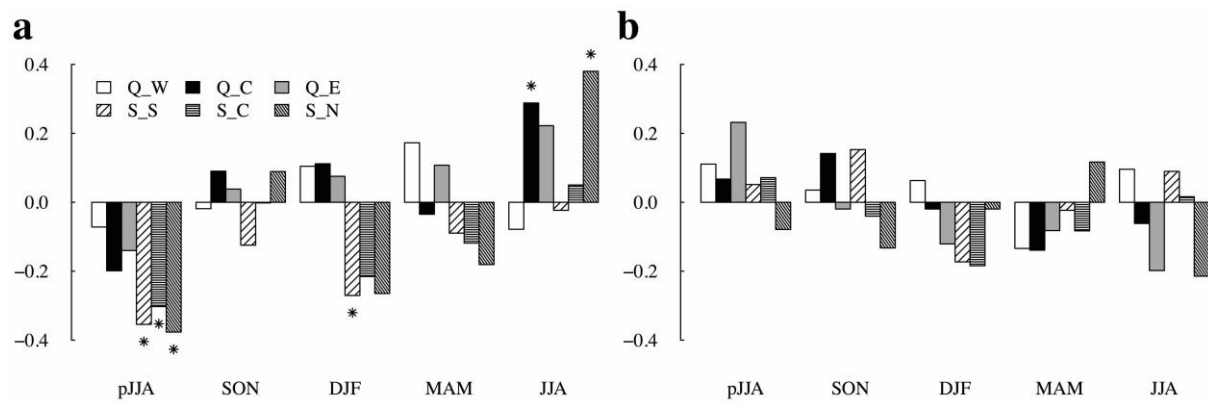
271 Some significant climate-growth associations were observed at the regional level (Fig. 2).  
272 Significant associations at the local level displayed strong spatial patterns and revealed  
273 heterogeneous within-region growth responses (Figs. 3 and 4). Moving correlations revealed  
274 numerous shifts in the significance of climate-growth associations around 1980 (Fig. 5).

#### 275 *3.1.1 Quebec*

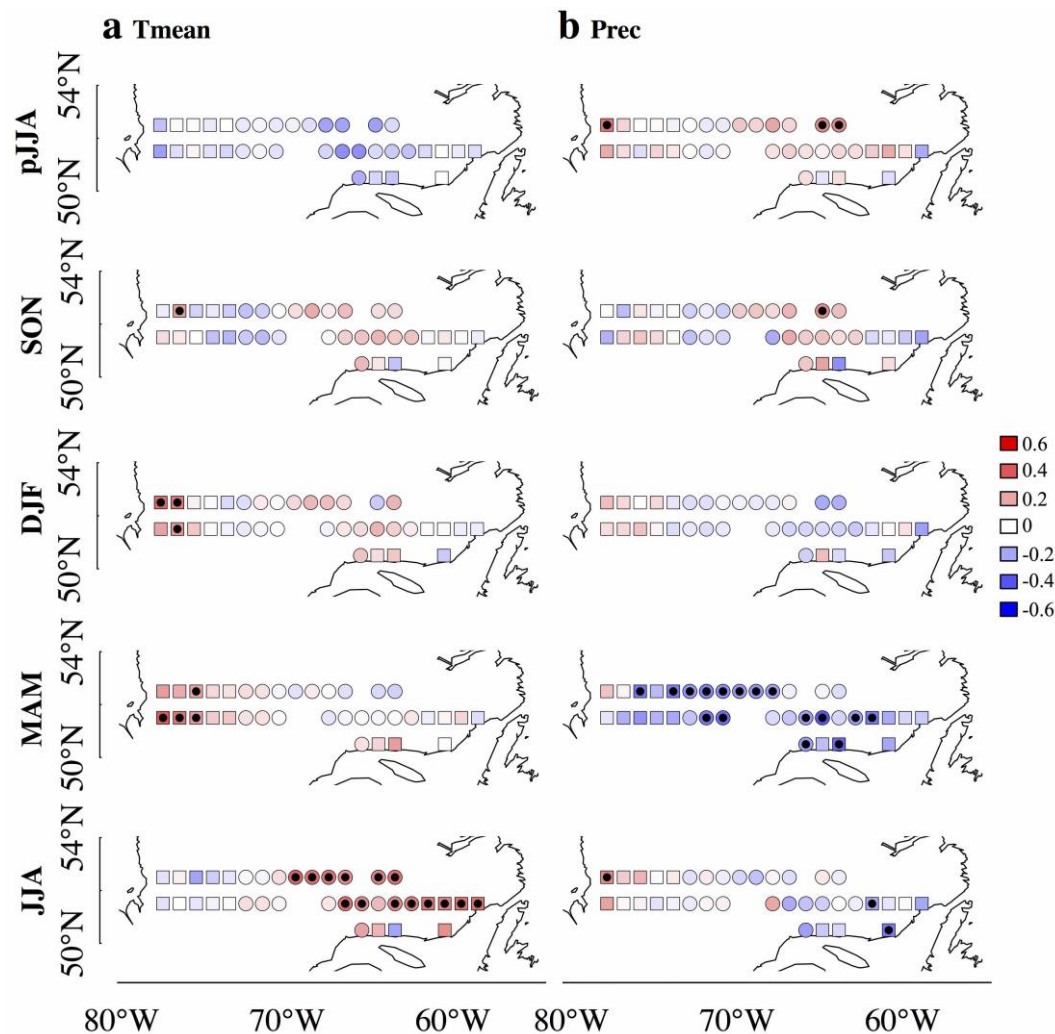
276 No significant climate-growth associations were observed at the regional level in western  
277 boreal Quebec over the entire study period (Fig. 2). Some significant positive responses to  
278 previous winter and current spring temperatures were observed at the local level, but these  
279 concerned a minority of cells (Fig. 3). Moving correlations revealed that Q\_W significantly  
280 correlated with previous summer precipitation (negatively) before the 1970s, with previous  
281 winter temperatures (positively) from the 1970s and with current spring temperatures  
282 (positively) from 1980 (Fig. 5).

283 Tree growth in central boreal Quebec significantly and positively correlated with current  
284 summer temperatures at the regional and local levels (Figs. 2 and 3). Numerous negative  
285 correlations between tree growth and spring precipitation were observed at the local level  
286 (Fig. 3). Moving correlations revealed an emerging correlation between Q\_C and previous  
287 winter temperatures in the early 1970s (significant during most intervals up to most recent  
288 years) (Fig. 5).

289 No significant climate-growth associations were observed in eastern boreal Quebec at the  
 290 regional level (Fig. 2). At the local level, some positive significant correlations with current  
 291 summer temperatures were observed (Fig. 3). Moving correlations revealed that Q\_E  
 292 correlated significantly and positively with current summer temperatures up to the early 1970s  
 293 (Fig. 5).  
 294



295 **Fig. 2.** Tree growth responses to seasonal temperature averages (a) and precipitation sums (b)  
 296 at the regional level over the 1950-2008 period, as revealed by correlation analyses. Analyses  
 297 were computed between the six regional chronologies (Q\_W, Q\_C, and Q\_E in NA; and S\_S,  
 298 S\_C and S\_N in NE) and seasonal climate data. Climate data were first extracted from the  
 299 CRU TS 3.24 1° x 1° (Harris *et al.*, 2014) for each grid cell and then aggregated at the  
 300 regional level by a robust bi-weighted mean. Seasons included previous summer (pJJA),  
 301 previous autumn (SON), winter (DJF); current spring (MAM) and current summer (JJA).  
 302 Significant correlations ( $P < 0.05$ ) are marked with a star.  
 303



304

305 **Fig. 3.** Tree growth responses to seasonal temperature averages (a) and precipitation sums (b)  
 306 at the local level over the 1950-2008 period in Quebec, as revealed by correlation analyses.  
 307 Analyses were computed between grid cell chronologies and local seasonal climate data  
 308 extracted for each grid cell from the CRU TS 3.24 1° x 1° (Harris *et al.*, 2014). Seasons  
 309 included previous summer (pJJA), previous autumn (SON), winter (DJF); current spring  
 310 (MAM) and current summer (JJA). To visualize separation between regional clusters (Q\_W,  
 311 Q\_C, and Q\_E, cf. Fig. 1) correlation values at Q\_C grid cells are plotted with circles.  
 312 Significant correlations ( $P < 0.05$ ) are marked with a black dot.

313

### 314 3.1.2 Sweden

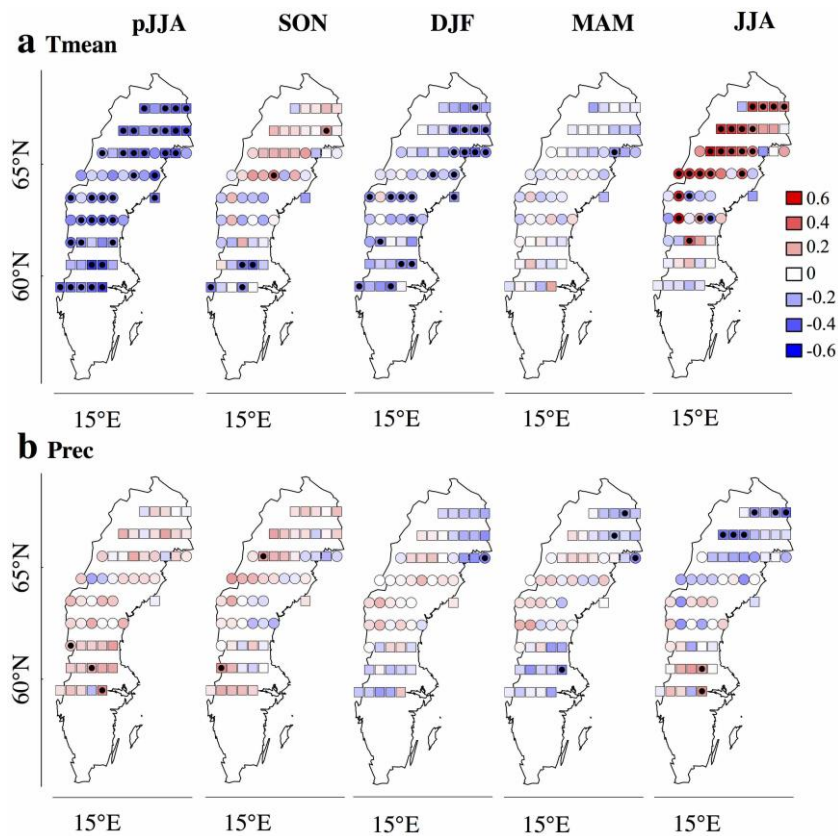
315 Tree growth in southern boreal Sweden correlated significantly and negatively with previous  
 316 summer and winter temperatures at the regional and local levels, the correlation with winter  
 317 temperatures concerning however only a minority of cells (Figs. 2 and 4). Moving

318 correlations indicated that the negative association with previous summer temperatures  
319 remained significant up to the early 1990s and that the negative association with winter  
320 temperatures emerged after 1980 (Fig. 5).

321 In central boreal Sweden, tree growth significantly and negatively correlated with previous  
322 summer temperatures both at the regional and local levels (Figs. 2 and 4). Some additional  
323 significant correlations with winter temperatures (negative) and with current summer  
324 temperatures (positive) were observed at the local level (Fig. 4). Moving correlation analyses  
325 revealed a significant positive correlation between S\_C and current summer temperatures that  
326 dropped and became non-significant at the end of the study period (Fig. 5). In addition, the  
327 correlation between S\_C and previous summer precipitation shifted from significantly  
328 negative to significantly positive during the 1980s (Fig. 5). S\_C became significantly and  
329 negatively correlated with previous summer temperatures after the 1980s and stopped being  
330 significantly and negatively correlated with previous autumn precipitation and with winter  
331 temperatures at the end of the 1970s (Fig. 5).

332 Tree growth in northern boreal Sweden correlated significantly with previous summer  
333 (negatively) and current summer temperatures (positively) both at the regional and local  
334 levels (Figs. 2 and 4). At the local level, tree growth in some cells significantly and negatively  
335 correlated with winter temperatures (Fig. 4). Significant and negative responses to current  
336 summer precipitation were observed at northernmost cells (Fig. 4). Moving correlations  
337 revealed that the positive association with current summer temperatures was only significant  
338 at the beginning and at the end of the study period (Fig. 5). After the 1980s, significant  
339 positive associations with previous autumn temperatures emerged (Fig. 5) and the significant  
340 negative association with winter temperatures disappeared.



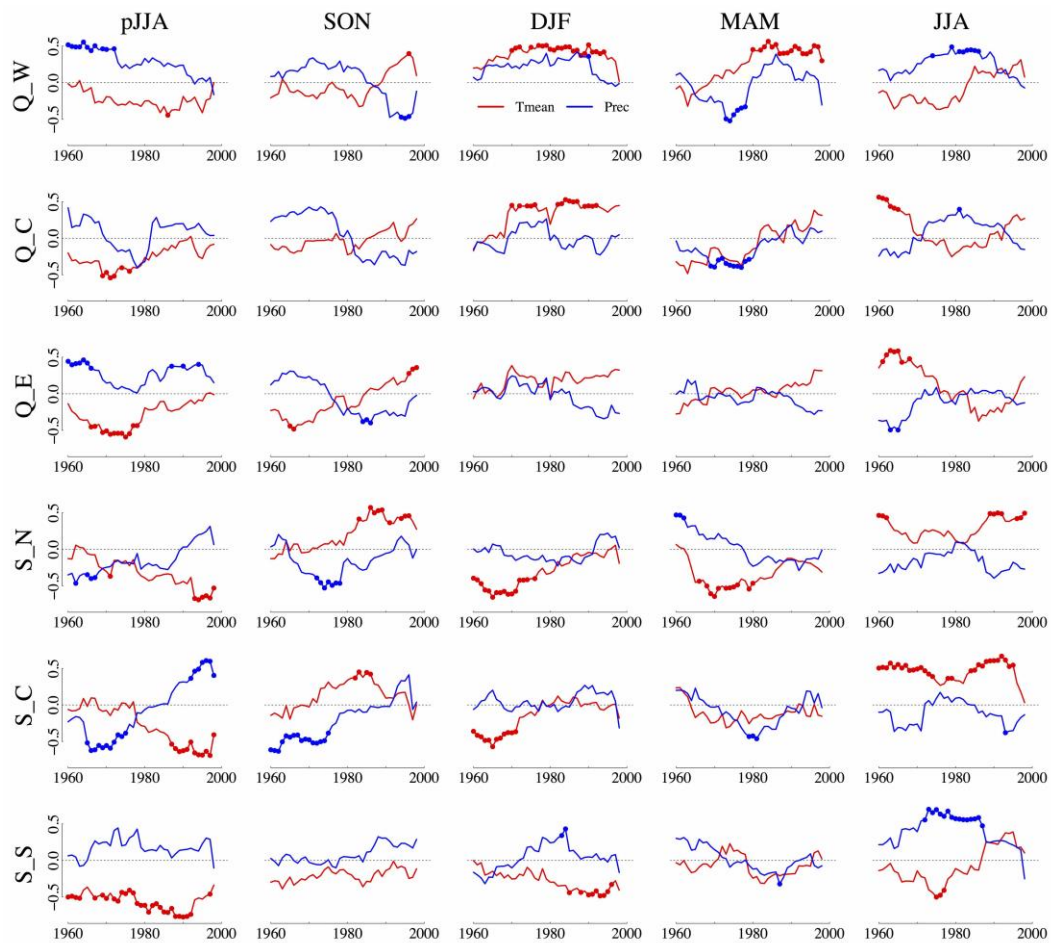


341

342 **Fig. 4.** Tree growth responses to seasonal temperature averages (a) and precipitation sums (b)  
 343 at the local level over the 1950-2008 period in Sweden, as revealed by correlation analyses.

344 Analyses were computed between grid cell chronologies and local seasonal climate data  
 345 extracted for each grid cell from the CRU TS 3.24  $1^\circ \times 1^\circ$  (Harris *et al.*, 2014). Seasons  
 346 included previous summer (pJJA), previous autumn (SON), winter (DJF); current spring  
 347 (MAM) and current summer (JJA). To visualize the separation between regional clusters  
 348 (S\_S, S\_C, and S\_N, cf. Fig. 1) correlation values at S\_C grid cells are plotted with circles.  
 349 Significant correlations ( $P < 0.05$ ) are marked with a black dot.

350



351

352 **Fig. 5.** Moving correlations between regional seasonal temperature averages (red lines) and  
 353 precipitation sums (blue lines), and the six regional chronologies (Q\_W, Q\_C, and Q\_E in  
 354 NA; and S\_S, S\_C and S\_N in NE) over the 1950-2008 period. Climate data were first  
 355 extracted for each grid cell from the CRU TS 3.24 1° x 1° (Harris *et al.*, 2014) and then  
 356 aggregated at the regional level by robust bi-weighted mean. Seasons included previous  
 357 summer (pJJA), previous autumn (SON), winter (DJF); current spring (MAM) and current  
 358 summer (JJA). Moving correlations were calculated using 21-yr windows moved one year at a  
 359 time and are plotted using the central year of each window. Windows of significant  
 360 correlations ( $P < 0.05$ ) are marked with a dot.

361

### 362 **3.2 Links between tree growth patterns and large-scale indices**

363 Some significant associations were found between tree growth and large-scale indices (Figs.  
 364 6, 7, and 8). Moving correlation analyses revealed some shifts from pre-1980 insignificant to

365 post-1980 significant correlations (Fig. 9). The seasonal indices involved in these shifts varied  
366 across regional chronologies.

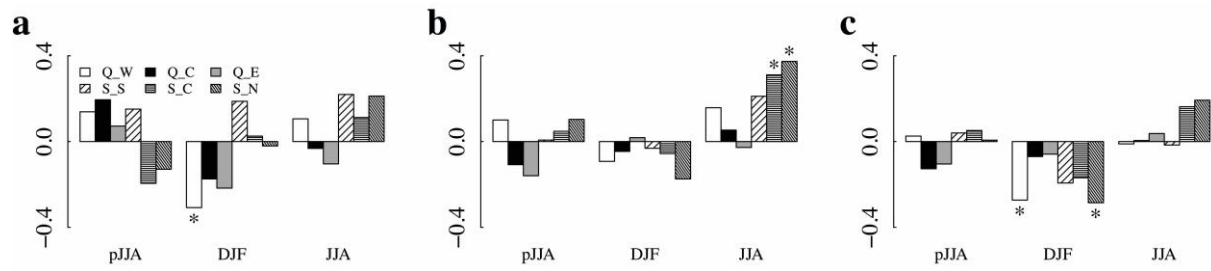
367

### 368 *3.2.1 Quebec*

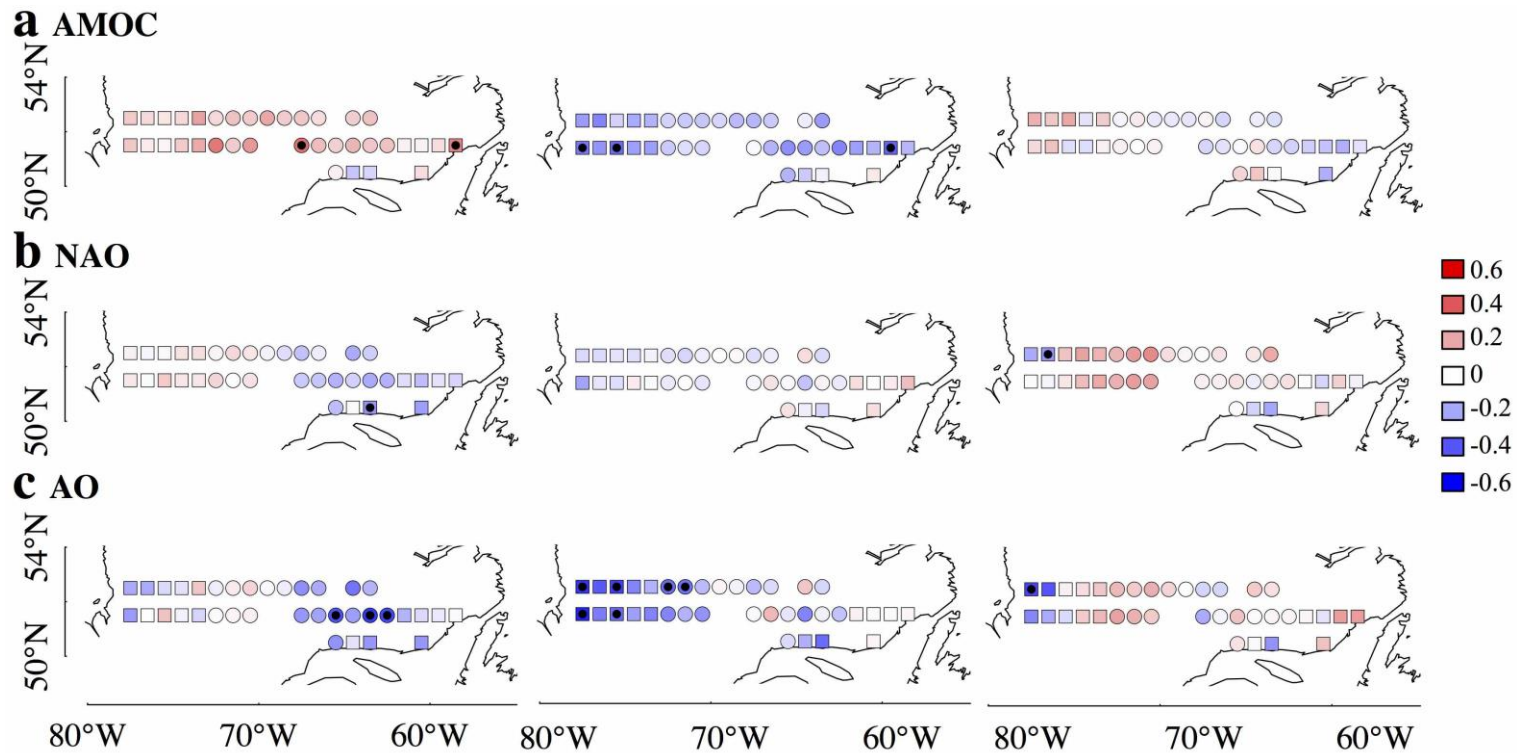
369 Tree growth in western boreal Quebec was significantly and negatively associated with the  
370 winter AMOC and the winter AO indices at the regional level (Fig. 6). At the local level,  
371 these associations concerned, however, a minority of cells (Fig. 7). Moving correlations  
372 revealed that the regional negative association with winter AMOC was only significant in the  
373 most recent part of the study period (Fig. 9). Significant negative correlations between Q\_W  
374 and current summer NAO and AO indices were observed from the 1980s up to the most  
375 recent years, at which point they show a steep increase and become non-significant (Fig. 9).

376 In central boreal Quebec, no significant associations between tree growth and seasonal  
377 indices were identified at the regional or local level (Figs. 6 and 7). Moving correlations  
378 indicated significant negative correlations with previous summer NAO and AO indices of  
379 during the 1970s, with winter NAO and AO indices during the 1980s and with current  
380 summer NAO and AO indices from the 1980s up to the most recent years (Fig. 9).

381 No significant association was identified between large-scale indices and tree growth  
382 in eastern boreal Quebec (Figs. 6, 7, and 9).



385 **Fig. 6.** Correlation between seasonal AMOC (a), NAO (b), and AO (c) indices and the six  
 386 regional chronologies (Q\_W, Q\_C, and Q\_E in NA; and S\_S, S\_C and S\_N in NE). Seasonal  
 387 indices include previous summer (pJJA), winter (DJF), and current summer (JJA), and were  
 388 calculated as mean of monthly indices. Correlations were calculated over the 1961-2005  
 389 period for AMOC, and over the 1950-2008 period for NAO and AO. Significant correlations  
 390 ( $P < 0.05$ ) are marked with a star.



391

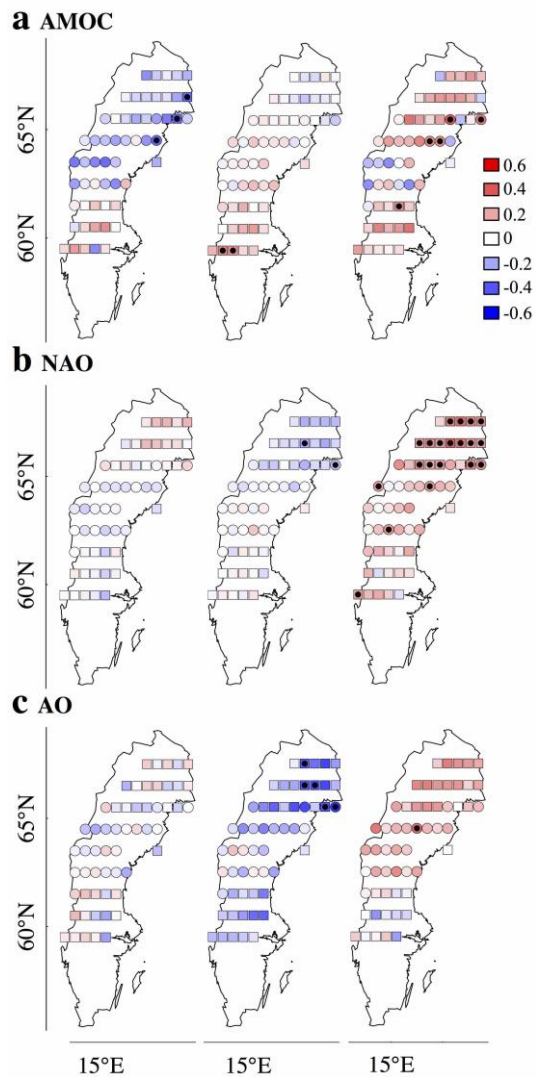
392 **Fig. 7.** Correlation between seasonal AMOC (a), NAO (b), and AO (c) indices, and growth patterns at the local level in Quebec. Seasonal indices  
 393 include previous summer (left-hand panels), winter (middle panels), and current summer (right-hand panels), and were calculated as mean of  
 394 monthly indices. Correlations were calculated over the 1961-2005 period for AMOC, and over the 1950-2008 period for NAO and AO. To  
 395 visualize the separation between regional clusters, correlation values at Q\_C grid cells are plotted with circles. Significant correlations ( $P < 0.05$ )  
 396 are marked with a black dot.

397 3.2.2 *Sweden*

398 No significant association between tree growth in southern boreal Sweden and seasonal large-  
399 scale indices was identified at the regional or local level (Figs. 6 and 8). Moving correlations  
400 revealed, however, significant negative associations between S\_S and the winter AMOC  
401 index before the 1980s (Fig. 9).

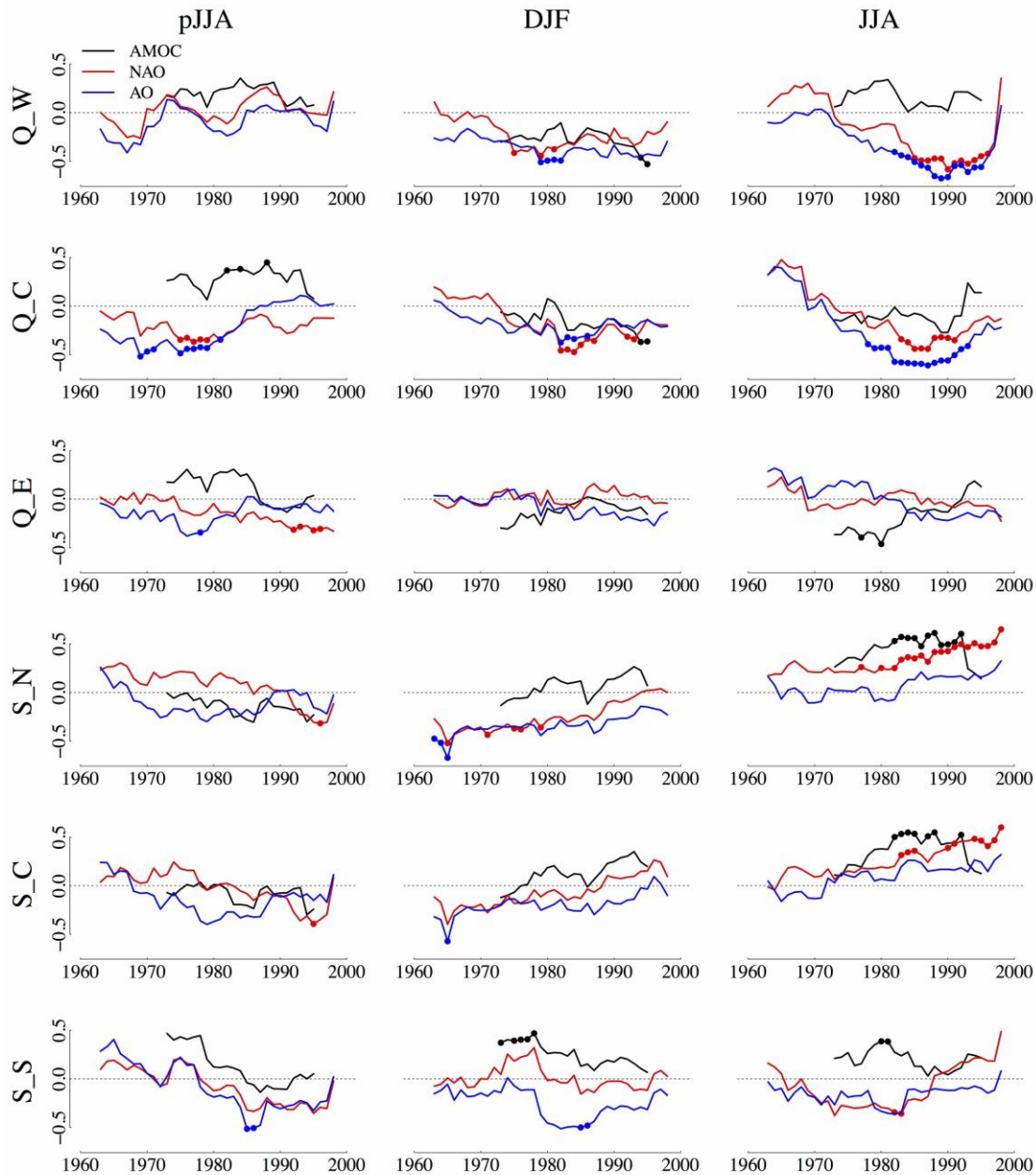
402 In central boreal Sweden, tree growth significantly and positively correlated with the current  
403 summer NAO index at the regional level (Fig. 6). At the local level, this correlation  
404 concerned, however, a minority of cells (Fig. 8). Moving correlations revealed that the  
405 significant positive association with the current summer NAO index emerged in the early  
406 1980s (Fig. 9) and that S\_C significantly correlated with the current summer AMOC index  
407 during the 1980s (Fig. 9).

408 In northern boreal Sweden, tree growth significantly correlated with the current summer NAO  
409 index (positively) and with the winter AO index (negatively) at the regional level (Fig. 6). At  
410 the local level, the positive association with summer NAO concerned a large majority of cells  
411 and the negative association with the winter AO index concerned only very few cells (Fig. 8).  
412 Moving correlation analyses indicated that the positive association between S\_N and the  
413 current summer NAO index was only significant after the 1980s and that S\_N significantly  
414 correlated with current summer AMOC during most of the 1980s (Fig. 9).



415

416 **Fig. 8.** Correlation between seasonal AMOC (a), NAO (b), and AO (c) indices, and growth  
 417 patterns at the local level in Sweden. Seasonal indices were calculated as mean of monthly  
 418 indices and include previous summer (left-hand panels), winter (middle panels), and current  
 419 summer (right-hand panels). Correlations were calculated over the 1961-2005 period for  
 420 AMOC, and over the 1950-2008 period for NAO and AO. To visualize the separation  
 421 between regional clusters, correlation values at S\_C grid cells are plotted with circles.  
 422 Significant correlations ( $P < 0.05$ ) are marked with a black dot.



423

424 **Fig. 9.** Moving correlations between previous summer (pJJA; left-hand panels), winter (DJF;  
 425 middle panels) and current summer (JJA; right-hand panels) large-scale indices, and the six  
 426 regional chronologies (Q\_W, Q\_C, and Q\_E in NA; and S\_S, S\_C and S\_N in NE). Large-  
 427 scale indices include AMOC (black), NAO (red), and AO (blue). Moving correlations were  
 428 calculated using 21-yr windows moved one year at a time and are plotted using the central  
 429 year of each window. Correlations were calculated over the 1961-2005 period for AMOC,  
 430 and over the 1950-2008 period for NAO and AO. Windows of significant correlations ( $P <$   
 431 0.05) are marked with a dot.

432



## 433 **4 DISCUSSION**

### 434 **4.1 Spatial aggregation of tree growth data**

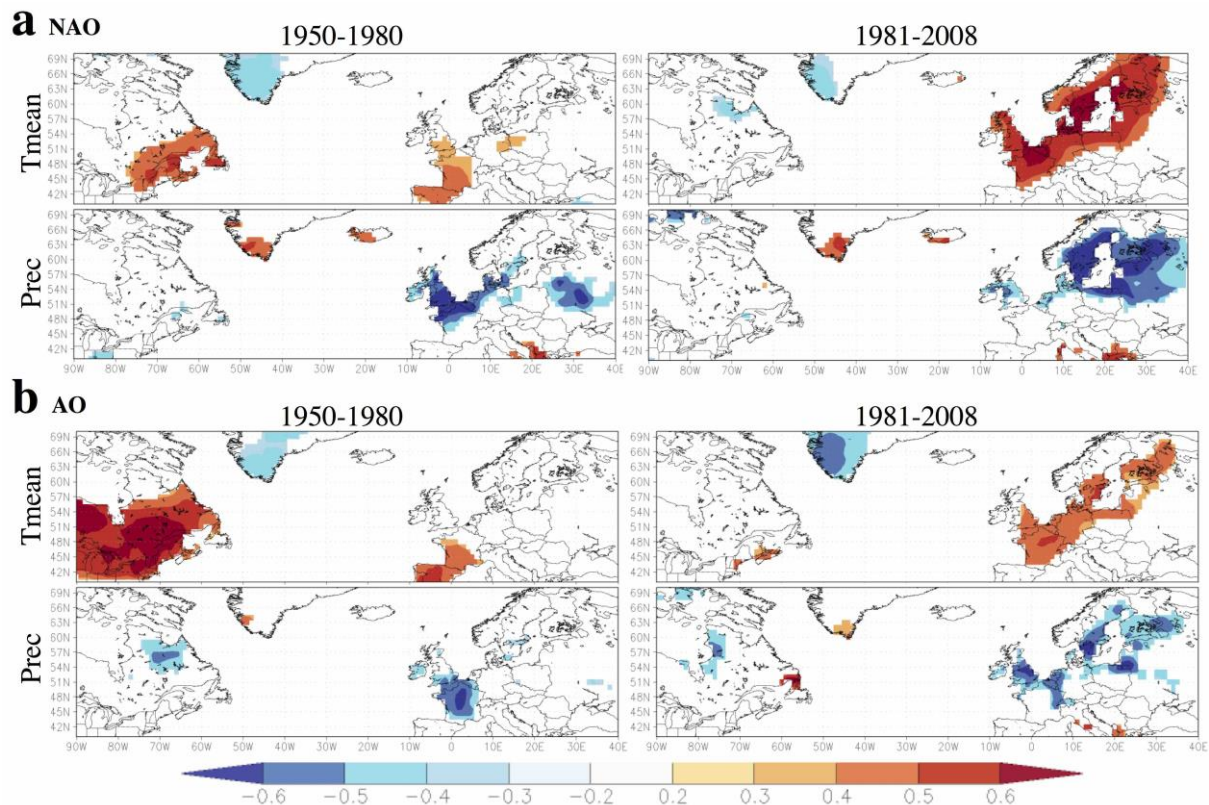
435 The high correlation between the regional chronologies in NE (Appendix S1), especially  
436 between the central and northern chronologies, could have supported the construction of one  
437 single boreal Sweden-wide regional chronology. Climate-growth analyses at the regional and  
438 local level revealed, nevertheless, clear differences across space in tree growth sensitivity to  
439 climate (Fig. 4) and to large-scale indices (Fig. 8), with a higher sensitivity in northernmost  
440 forests. The aggregation of tree growth data across space, even if based on objective similarity  
441 statistics (Appendix S1), may, therefore, mask important local differences in climate-growth  
442 interactions (Macias *et al.* 2004). Our results demonstrate that spatial aggregation should not  
443 be performed without accounting for bioclimatic domains especially when studying climate-  
444 growth interactions. In practice, one should at least check that a spatial similarity in tree  
445 growth patterns is associated with spatial similarity in seasonal climate. The use of both the  
446 regional and local scales regarding climate-growth interactions, as in the present study, is,  
447 therefore, recommended to exhaustively and more precisely capture cross-scale diverging and  
448 emerging tree growth patterns and sensitivity to climate.

449

### 450 **4.2 Post-1980 shifts towards significant influence of large-scale indices on boreal tree** 451 **growth**

452 The emergence of a post-1980 significant positive tree growth response to the current summer  
453 NAO index in central and northern boreal Sweden (Fig. 9) appears to be linked to spatial  
454 variability in the NAO influence on seasonal climate (Fig. 10). Summer NAO has had little to  
455 no influence on summer climate variability over the entire period 1950-2008 in boreal Quebec  
456 or Sweden (Appendix S4). However, the partitioning of the period into two sub-periods of  
457 similar length (1950-1980 and 1981-2008) revealed a northeastward migration of the

458 significant-correspondence field between the summer NAO index and local climate,  
 459 particularly in NE (Fig. 10). Over the 1981-2008 period, the summer NAO index was  
 460 significantly and positively associated with temperature and negatively with precipitation in  
 461 boreal Sweden (Fig. 10). Higher growing-season temperatures, induced by a higher summer  
 462 NAO, might have promoted the growth of temperature-limited Swedish boreal forest  
 463 ecosystems, explaining recent positive response of tree growth to this large-scale index in the  
 464 central and northern regions (Fig. 9). The northeastward migration of the NAO-climate spatial  
 465 field may be an early sign of a northward migration of the North Atlantic Gulf stream (Taylor  
 466 & Stephens, 1998) or a spatial reorganization of the Icelandic-low and Azores-high pressure  
 467 NAO's nodes (Portis *et al.*, 2001; Wassenburg *et al.*, 2016). The August Northern  
 468 Hemisphere Jet over NE reached its northernmost position in 1976 but thereafter moved  
 469 southward, despite increasing variability in its position (Trouet *et al* 2018). This southward  
 470 migration of the jet may weaken the strength of the observed post-1980 positive association  
 471 between boreal tree growth and the summer NAO index in NE in the coming decades.



473 **Fig. 10.** Correspondence between summer NAO (a) and AO (b) indices and local summer  
474 climate (mean temperature and total precipitation) between 1950 and 1980 (left-hand panels)  
475 and between 1981 and 2008 (right-hand panels). NAO and AO indices over the 1950-2008  
476 period were extracted from NOAA's climate prediction center. Summer mean temperature  
477 and total precipitation are those of CRU TS 3.24 1° x 1° (Harris *et al.*, 2014). All correlations  
478 were computed in the KNMI Climate Explorer (<https://climexp.knmi.nl> (Trouet & Van  
479 Oldenborgh, 2013)). Indices and climate variables were normalized (linear regression) prior  
480 to analyses. Only correlations significant at  $P < 0.05$  are plotted.

481

482         The post-1980 significant negative associations between tree growth and summer  
483 NAO and AO indices in boreal Quebec are more challenging to interpret. There was no  
484 evident significant tree growth response to summer temperature in these regions when  
485 analyzed over the full 1950-2008 period (Fig. 4). Yet, some significant positive associations  
486 between tree growth and temperatures were observed with winter temperatures from the  
487 1970s (in central Quebec) and with spring temperatures from the 1980s (in western Quebec  
488 only) (Fig. 5). These associations indicate that tree growth in boreal Quebec has been limited  
489 by winter and spring climate since the 1970s and 1980s, respectively. Below-average summer  
490 temperatures induced by high summer NAO and AO may exacerbate the sensitivity of tree  
491 growth to low temperatures. Noting that no significant post-1980 association was observed  
492 between temperature and summer NAO and AO indices in Quebec (Fig. 10), the emerging  
493 negative tree growth response to summer NAO and AO indices may indicate a complex  
494 interplay between large-scale indices and air mass dynamics and lagged effects over several  
495 seasons (Boucher *et al.*, 2017).

496         In western Quebec, tree growth was negatively influenced by the winter AMOC index  
497 at the regional level (Fig. 6). This relationship appears to be linked to a significant positive  
498 association between tree growth and spring temperature (Figs. 5 and 9). Positive winter  
499 AMOC indices are generally associated with cold temperatures in Quebec, and particularly so  
500 in the West (Appendix S4). Positive winter AMOC indices are associated with the dominance

501 of dry winter air masses of Arctic origin over Quebec, and may thereby delay the start of the  
502 growing season and reduce tree-growth potential.

503 Forest dynamics in NA have been reported to correlate with Pacific Ocean indices  
504 such as the Pacific Decadal Oscillation (PDO) or the El-Nino Southern Oscillation (ENSO),  
505 particularly through their control upon fire activities (Macias Fauria & Johnson 2006, Le Goff  
506 *et al.*, 2007). These indices have not been investigated in the present study but might present  
507 some additional interesting features.

508

### 509 **4.3 Contrasting climate-growth associations among boreal regions**

510 Post-1980 shifts in tree growth sensitivity to seasonal climate differed among boreal regions.

511 In NA, we observed the emergence of significantly positive growth responses to winter and

512 spring temperatures. In NE, observed post-1980 shifts mainly concerned the significance of

513 negative growth responses to previous summer and winter temperatures. Warmer

514 temperatures at boreal latitudes have been reported to trigger contrasting growth responses to

515 climate (Wilmking *et al.*, 2004) and to enhance the control of site factors upon growth

516 (Nicklen *et al.*, 2016). This is particularly true with site factors influencing soil water

517 retention, such as soil type, micro-topography, and vegetation cover (Düthorn *et al.*, 2013).

518 Despite a generalized warming at high latitudes (Serreze *et al.*, 2009), no increased sensitivity

519 of boreal tree growth to precipitation was identified in the present study, except in central

520 Sweden where tree growth became positively and significantly correlated to previous summer

521 precipitation (Fig. 5). This result underlines that temperature remains the major-growth

522 limiting factor in our study regions.

523 The observed differences in tree growth response to winter temperature highlight

524 diverging non-growing season temperature constraints on boreal forest growth. While warmer

525 winters appear to promote boreal tree growth in NA, they appear to constrain tree growth in

526 boreal NE. Such opposite responses to winter climate from two boreal tree species of the  
527 same genus might be linked to different winter conditions between Quebec and Sweden. In  
528 NA, winters conditions are more continental and harsher than in NE (Appendix S5). Warmer  
529 winters may therefore stimulate an earlier start of the growing season and increase growth  
530 potential (Rossi *et al.*, 2014). However, warmer winters, combined with shallower snow-pack,  
531 have been shown to induce a delay in the spring tree growth onset, through lower thermal  
532 inertia and a slower transition from winter to spring (Contosta *et al.*, 2017). This phenomenon  
533 might explain the negative association between tree growth and winter temperatures observed  
534 in NE.

535         The post-1970s growth-promoting effects of winter and spring temperature in NA  
536 (Fig. 5) suggest, as earlier reported by Charney *et al.* (2016) and Girardin *et al.* (2016), that,  
537 under sufficient soil water availability and limited heat stress conditions, tree growth at mid-  
538 to high-latitudes can increase in the future. However, warmer winters may also negatively  
539 affect growth by triggering an earlier bud break and increasing risks of frost damages to  
540 developing buds (Cannell and Smith, 1986) or by postponing the start of the growing season  
541 (see above, Contosta *et al.*, 2017). This might provide an argument against a sustained  
542 growth-promoting effect of higher seasonal temperatures (Girardin *et al.*, 2014).

543

#### 544 **4.4 Gradients in the sensitivity of tree growth to North Atlantic Ocean dynamics across** 545 **boreal Quebec and Sweden**

546 Trees in western and central boreal Quebec, despite being furthest away from the North  
547 Atlantic Ocean in comparison to trees in eastern boreal Quebec, were the most sensitive to  
548 oceanic and atmospheric dynamics, and particularly to current summer NAO and AO indices  
549 after the 1970s. In these two boreal regions, tree growth responses to large-scale indices were  
550 stronger and more spatially homogeneous than tree growth responses to regional climate. This

551 suggests that growth dynamics in western and central boreal Quebec, despite being mainly  
552 temperature-limited, can be strongly governed by large-scale oceanic and atmospheric  
553 dynamics (Boucher *et al.*, 2017). The tree growth sensitivity to the winter AMOC index  
554 observed at regional level in western boreal Quebec might directly emerge from the  
555 correspondence between AMOC and winter snow fall. Western boreal Quebec is the driest  
556 and most fire-prone of the Quebec regions studied here. Soil water availability in this region  
557 strongly depends on winter precipitation. High winter AMOC indices are associated with the  
558 dominance of Arctic air masses over NA and leads to decreased snowfall (Appendix S4).  
559 Large-scale indices, through their correlation with regional fire activity, can also possibly  
560 override the direct effects of climate on boreal forest dynamics (Drobyshev *et al.*, 2014;  
561 Zhang *et al.*, 2015). Fire activity in NA strongly correlates with variability in atmospheric  
562 circulation, with summer high-pressure anomalies promoting the drying of forest fuels and  
563 increasing fire hazard (Skinner *et al.*, 1999, Macias Fauria & Johnson 2006) and low-pressure  
564 anomalies bringing precipitation and decreasing fire activity.

565         In Sweden, the northernmost forests were the most sensitive to North Atlantic Ocean  
566 dynamics, particularly to the summer NAO (Fig. 8). These high-latitude forests, considered to  
567 be ‘Europe’s last wilderness’ (Kuuluvainen *et al.*, 2017), are experiencing the fastest climate  
568 changes (Hansen *et al.*, 2010). Numerous studies have highlighted a correspondence between  
569 tree growth and NAO (both winter and summer) across Sweden (D'Arrigo *et al.*, 1993; Cullen  
570 *et al.*, 2001; Linderholm *et al.*, 2010), with possible shifts in the sign of this correspondence  
571 along north-south (Linderholm *et al.*, 2001) and west-east gradients (Linderholm *et al.*, 2003).  
572 Our results identified a post-1980 positive correspondence between tree growth and summer  
573 NAO, spatially restricted to the northernmost regions (Figs. 8 and 9). This emerging  
574 correspondence appears linked to the combination of a growth-promoting effect of higher  
575 temperature at these latitudes (Fig. 5) and a northeastward migration of the spatial

576 correspondence between NAO and local climate (Fig. 10). Boreal forests of Quebec (western  
577 and central) and Sweden (central and northern) emerged as regions sensitive to large-scale  
578 climate dynamics. We, therefore, consider them as suitable for a long-term survey of impacts  
579 of ocean-atmosphere dynamics on boreal forest ecosystems.

580

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## 596 **Appendix A – Supplementary data**

597 Supplementary data to this article can be found online at

598 <https://doi.org/10.1902/j.gloplacha.2018.03.006>

## 599 **References**

600 Affymetrix (2002) Appendix I- Statistical Algorithms Description Document

- 601 Akaike H. (1974). A new look at the statistical model identification. *IEEE Trans. Autom.*  
602 *Control* **16**, 716-723.
- 603 Bala G., Caldeira K., Wickett M., Phillips T.J., Lobell D.B., Delire C. & Mirin A. (2007)  
604 Combined climate and carbon-cycle effects of large-scale deforestation. *Proc. Natl.*  
605 *Acad. Sci. U. S. A.*, **104**, 6550–6555.
- 606 Baldwin M.P. & Dunkerton T.M. (1999) Propagation of the Arctic Oscillation from the  
607 stratosphere to the troposphere. *J. Geophys. Res.* **104**, 30,937-30,946.
- 608 Betts R.A. (2000) Offset of the potential carbon sink from boreal forestation by decreases in  
609 surface albedo. *Nature* **408**, 187-190.
- 610 Boucher E., Nicault A., Arseneault D., Bégin Y. & Pasha M. (2017) Decadal variations in  
611 eastern Canada's taiga wood biomass production forced by ocean-atmosphere  
612 interactions. *Sci. Rep.* **7**, 2457.
- 613 Brant J.P., Flanningan M.D., Maynard D.G., Thompson I.D. & Volney W.J.A. (2013) An  
614 introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and  
615 environmental issues. *Environ. Rev.* **21**, 207–226.
- 616 Briffa K.R., Schweingruber F.H., Jones P.D., Osborn T.J., Shiyatov S.G. & Vaganov E.A.  
617 (1998) Reduced sensitivity of recent tree-growth to temperature at high northern  
618 latitudes. *Nature*, **391**, 678-682.
- 619 Cannell M.G.R. & Smith R.I. (1986) Climatic warming, spring budburst, and frost damage on  
620 trees. *J Appl Ecol*, **23**, 177–191.
- 621 Charney N.D., Babst F., Poulter B., Record S., Trouet V.M., Frank D., Enquist B.J. & Evans  
622 M.E. (2016) Observed forest sensitivity to climate implies large changes in 21st  
623 century North American forest growth. *Ecology Letters*, **19**, 1119-1128
- 624 Chen D. & Hellström C. (1999) The influence of the North Atlantic Oscillation on the  
625 regional temperature variability in Sweden: spatial and temporal variations. *Tellus A*,  
626 **51**, 505-516.
- 627 Contosta A.R., Adolph A., Burchsted D., Burakowski E., Green M., Guerra D., Albert M.,  
628 Dibb J., Martin M., McDowell W.H., Routhier M., Wake C., Whitaker R. & Wollheim  
629 W. (2017) A longer vernal window: the role of winter coldness and snowpack in  
630 driving spring transitions and lags. *Glob Change Biol*, **23**, 1610-1625.
- 631 Cook E.R. & Peters K. (1981) The smoothing spline: an approach to standardizing forest  
632 interior tree-ring width series for dendroclimatic studies *Tree-Ring Bull*, **41**, 45-53.
- 633 Cullen H.M., D'Arrigo R.D. & Cook E.R. (2001) Multiproxy reconstructions of the North  
634 Atlantic Oscillation. *Paleoceanography*, **16**, 27-39.
- 635 D'Arrigo R.D., Cook E.R., Jacoby G.C. & Briffa K.R. (1993) NAO and sea surface  
636 temperature signatures in tree-ring records from the North Atlantic sector. *Quat Sci*  
637 *Rev*, **12**, 431-440.
- 638 de Wit H.A., Bryn A., Hofgaard A., Karstensen J., Kvalevag M.M. & Peters G.P. (2014)  
639 Climate warming feedback from mountain birch forest expansion: Reduced albedo  
640 dominates carbon uptake. *Glob Change Biol*, **20**, 2344-55.
- 641 Drobyshev I., Guitard M.-A., Asselin H., Genries A. & Bergeron Y. (2014) Environmental  
642 controls of the northern distribution limit of yellow birch in eastern Canada. *Can J For*  
643 *Res*, **44**, 720-731.
- 644 Drobyshev I., Bergeron Y., Vernal A., Moberg A., Ali A.A. & Niklasson M. (2016) Atlantic  
645 SSTs control regime shifts in forest fire activity of Northern Scandinavia. *Sci Rep*, **6**,  
646 22532.
- 647 DÜthorn E, Holzkämper S., Timonen M. & Esper J. (2013) Influence of micro-site conditions  
648 on tree-ring climate signals and trends in central and northern Sweden. *Trees*, **27**,  
649 1395-1404.



650 Gauthier S., Bernier P., Kuuluvainen T., Shvidenko A.Z. & Schepaschenko D.G. (2015)  
651 Boreal forest health and global change. *Science*, **349**, 819-822.

652 Gerardin V. & McKenney D. (2001) Une classification climatique du Québec à partir de  
653 modèles de distribution spatiale de données climatiques mensuelles : vers une  
654 définition des bioclimats du Québec. *Direction du patrimoine écologique et du*  
655 *développement durable, ministère de l'Environnement, Québec,*

656 Girardin M.P., Guo X.J., De Jong R., Kinnard C., Bernier P. & Raulier F. (2014) Unusual  
657 forest growth decline in boreal North America covaries with the retreat of Arctic sea  
658 ice. *Glob Change Biol*, **20**, 851-66.

659 Girardin M.P., Bouriaud O., Hogg E.H., Kurz W., Zimmermann N.E., Metsaranta J.M., de  
660 Jong R., Frank D.C., Esper J., Buntgen U., Guo X.J. & Bhatti J. (2016) No growth  
661 stimulation of Canada's boreal forest under half-century of combined warming and  
662 CO<sub>2</sub> fertilization. *Proc Natl Acad Sci U S A*, **113**, E8406-E8414.

663 Hansen J., Ruedy R., Sato M. & Lo K. (2010) Global surface temperature change. *Rev*  
664 *Geophys*, **48**

665 Harris I., Jones P.D., Osborn T.J. & Lister D.H. (2014) Updated high-resolution grids of  
666 monthly climatic observations --- the CRU TS3.10 dataset. *Int J Climatol*, **34**, 623-  
667 642.

668 Hurrell J.W. (1995) Decadal trends in the north atlantic oscillation: regional temperatures and  
669 precipitation. *Science*, **269**, 676-9.

670 International Tree Ring Data Bank (ITRDB) (2016) Available at:  
671 <http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>  
672 (accessed 15 October 2014).

673 IPCC (2014) Intergovernmental Panel on Climate Change. Fifth assessment report climate  
674 change 2014. synthesis report---summary for policymakers. 1-35.

675 Jackson L.C., Kahana R., Graham T., Ringer M.A., Woollings T., Mecking J.V. & Wood  
676 R.A. (2015) Global and European climate impacts of a slowdown of the AMOC in a  
677 high resolution GCM. *Clim. Dyn.*, **45**, 3299-3316.

678 Karlsen S.R., Høgda K.A., Wielgolaski F.E., Tolvanen A., Tømmervik H., Poikolainen J. &  
679 Kubin E. (2009) Growing-season trends in Fennoscandia 1982–2006, determined from  
680 satellite and phenology data. *Clim Res*, **39**, 275-286.

681 Kuuluvainen T., Hofgaard A., Aakala T. & Jonsson B.G. (2017) North Fennoscandian  
682 mountain forests: History, composition, disturbance dynamics and the unpredictable  
683 future. *For Ecol Manage*, **385**, 140-149.

684 Le Goff H., Flannigan M.D., Bergeron Y. & Girardin M.P. (2007) Historical fire regime shifts  
685 related to climate teleconnections in the Waswanipi area, central Quebec, Canada. *Int.*  
686 *J. Wild Fire*. **16**, 607-618

687 Lenton T.M. (2011) Early warning of climate tipping points. *Nat Clim Chan*, **1**, 201-209.

688 Lenton T.M., Held H., Kriegler E., Hall J.W., Lucht W., Rahmstorf S. & Schellnhuber H.J.  
689 (2008) Tipping elements in the Earth's climate system. *P Natl Acad Sci USA*, **105**,  
690 1786-93.

691 Linderholm H.W., Solberg B. Ø. & Lindholm M. (2003) Tree-ring records from central  
692 Fennoscandia: the relationship between tree growth and climate along a west–east  
693 transect. *The Holocene*, **13**, 887-895

694 Linderholm H.W., Björklund J.A., Seftigen K., Gunnarson B.E., Grudd H., Jeong J.-H.,  
695 Drobyshev I. & Liu Y. (2010) Dendroclimatology in Fennoscandia – from past  
696 accomplishments to future potential. *Clim Past*, **9**, 93-114.

697 Lindholm M., Eggertsson O., Lovelius N., Raspopov O., Shumilov O. & Läänelaid A. (2001)  
698 Growth indices of North European Scots pine record the seasonal North Atlantic  
699 Oscillation. *Boreal Environ Res*, **6**, 275-284.

700 Macias M., Timonen M., Kirchhefer A.J., Lindholm M., Eronen M. & Gutiérrez E. (2004).  
701 Growth variability of Scots pine (*Pinus sylvestris*) along a west-east gradient across  
702 northern Fennoscandia: A dendroclimatic approach. *Arctic, Antarctic, and Alpine*  
703 *Research*, **36**, 565-574.

704 Macias Faurias M. & Johnson E.A. (2006) Large-scale climatic patterns control large  
705 lightning fire occurrence in Canada and Alaska forest regions. *J Geophys Res*, **111**,  
706 G04008, doi:10.1029/2006JG000181

707 Ministère des Ressources naturelles du Québec (2014) Norme d'inventaire écodendrométrie  
708 nordique. In: (ed. S.D. Fôrets.), p. 156 p. + 10 annexes.

709 Moen A. (1999) National Atlas of Norway. Vegetation. Norway Mapping Authority,  
710 Hønefoss.

711 Nicklen E.F., Roland C.A., Ruess R.W., Schmidt J.H. & Lloyd A.H. (2016) Local site  
712 conditions drive climate–growth responses of *Picea mariana* and *Picea glauca* in  
713 interior Alaska. *Ecosphere*, **7**

714 NOAA (2016) *National Oceanic and Atmospheric Administration*. Available at:  
715 <http://www.cpc.ncep.noaa.gov/data/> (accessed 01-09 2016).

716 Ols C., Hofgaard A., Bergeron Y. & Drobyshev I. (2016) Previous growing season climate  
717 controls the occurrence of black spruce growth anomalies in boreal forests of Eastern  
718 Canada. *Can J For Res*, **46**, 696-705.

719 Ottersen G., Planque B., Belgrano A., Post E., Reid P.C. & Stenseth N.C. (2001) Ecological  
720 effects of the North Atlantic Oscillation. *Oecologia*, **128**, 1-14.

721 Portis D.H., Walsh J.E., El Hamly M. & Lamb P.J. (2001) Seasonality of the North Atlantic  
722 Oscillation. *J Clim*, **14**, 2069-2078.

723 Rahmstorf S., Box J.E., Feulner G., Mann M.E., Robinson A., Rutherford S. & Schaffernicht  
724 E.J. (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning  
725 circulation. *Nat Clim Chan*, **5**, 475-480

726 Riksskogstaxeringen (2016) *Statistik om skog*. Available at:  
727 <http://www.slu.se/riksskogstaxeringen> (accessed 10 09 2014).

728 Robitaille A. & Saucier J.-P. (1998) *Paysages régionaux du Québec méridional*. Les  
729 Publications du Québec, Québec.

730 Rossi S., Girard M.J. & Morin H. (2014) Lengthening of the duration of xylogenesis  
731 engenders disproportionate increases in xylem production. *Glob Chang Bio*, **20**, 2261-  
732 2271

733 Serreze M.C., Barrett A.P., Stroeve J.C., Kindig D.N. and Holland M.M. (2009) The  
734 emergence of surface-based Arctic amplification, *The Cryosphere*, **3**, 11-19,  
735 <https://doi.org/10.5194/tc-3-11-2009>.

736 Sgubin G., Swingedouw D., Drijfhout S., Mary Y. & Bennadi A. (2017) Abrupt cooling over  
737 the North Atlantic in modern climate models. *Nat Commun*, **8**, 1-12.

738 Skinner W.R., Stocks B.J., Martell D.L., Bonsal B. & Shabbar A. (1999) The Association  
739 Between Circulation Anomalies in the Mid-Troposphere and Area Burned by Wildland  
740 Fire in Canada. *Theor Appl Climatol*, **63**, 89-105.

741 Solberg B.O., Hofgaard A. & Hytteborn H. (2002) Shifts in radial growth responses of coastal  
742 *Picea abies* induced by climatic change during the 20th century, central Norway.  
743 *Ecoscience* **9**, 79-88.

744 Student (1908). The probable error of the mean. *Biometrika*, **6**, 1-25.

745 Sveriges meteorologiska och hydrologiska institut (SMHI) (2016) *Sveriges Meteorologi:*  
746 *Temperatur och Nederbörd över 1961-1990*. Available at:  
747 <http://www.smhi.se/klimatdata/meteorologi/> (accessed 15 June 2016).

748 Taylor A.H. & Stephens J.A. (1998) The North Atlantic Oscillation and the latitude of the  
749 Gulf Stream. *Tellus*, **50A**, 134-141.

- 750 Trouet V. & Van Oldenborgh G.J. (2013) KNMI Climate Explorer: A web-based research  
751 tool for high-resolution paleoclimatology. *Tree-Ring Res*, **69**, 3-13.
- 752 Trouet V., Babst F. & Meko M. (2018) Recent enhanced high-summer North Atlantic Jet  
753 variability emerges from three-century context. *Nat Commun*, **9**: 180
- 754 Walker G.T. (1924) Correlation in seasonal variation of weather. IX. A further study of world  
755 weather. *Memoirs of the India Meteorological Department*, **24**, 275–333.
- 756 Wallace J.M. & Gutzler D.S. (1981) Teleconnections in the geopotential height field during  
757 the Northern Hemisphere Winter. *Mon Weather Rev*, **109**, 784-812.
- 758 Wassenburg J.A., Dietrich S., Fietzke J., Fohlmeister J., Jochum K.P., Scholz D., Richter  
759 D.K., Sabaoui A., Spotl C., Lohmann G., Andreae M.O. & Immenhauser A. (2016)  
760 Reorganization of the North Atlantic Oscillation during early Holocene deglaciation.  
761 *Nature Geosci*, **9**, 602-605.
- 762 Wettstein J.J. & Mearns L.O. (2002) The influence of the North Atlantic–Arctic Oscillation  
763 on mean, variance, and extremes of temperature in the Northeastern United States and  
764 Canada. *J Clim*, **15**, 3582-3600.
- 765 Wilmking M., Juday G.P., Barber V.A. & Zald H.S.J. (2004) Recent climate warming forces  
766 contrasting growth responses of white spruce at treeline in Alaska through temperature  
767 thresholds. *Glob Chang Biol*, **10**, 1724-1736.
- 768 Zang C. & Biondi F. (2015) treeclim: an R package for the numerical calibration of proxy-  
769 climate relationships. *Ecography*, **38**, 431-436.
- 770 Zhang Y., Bergeron Y., Zhao X.-H. & Drobyshhev I. (2015) Stand history is more important  
771 than climate in controlling red maple (*Acer rubrum* L.) growth at its northern  
772 distribution limit in western Quebec, Canada. *J Plant Ecol*, **8**, 368-379.
- 773 Zickfeld K., Eby M. & Weaver A.J. (2008) Carbon-cycle feedbacks of changes in the Atlantic  
774 meridional overturning circulation under future atmospheric CO<sub>2</sub>. *Glob Biogeochem*  
775 *Cycles*, **22**.
- 776