

1 **Climate variability in Poland (Central Europe) in the 16th century based on**
2 **multiproxy data**

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23

ABSTRACT

24 The article includes an overview of the current state of knowledge regarding climate in Poland (Central Europe) in the
25 16th century and its changes. For this purpose, we utilised all previously published reconstructions and five new
26 quantitative reconstructions incorporating dendrochronological data and documentary evidence. New
27 dendrochronological data were used to reconstruct the mean winter or late winter–early spring temperatures, while
28 documentary evidence enabled the reconstruction of mean winter (DJF) and summer (JJA) temperatures. The climate
29 of Poland in the 16th century, as reconstructed from documentary evidence, was colder than it is today (1991–2020),
30 particularly in winter (by 3.6 °C). In summer, it was only 0.7 °C colder than today. Compared to the average for the
31 entire 20th century, however, the summer average in the 16th century was 0.3 °C warmer, whereas the winter average
32 was 2.5 °C colder. In both dendrochronological reconstructions of the temperature of south-eastern Poland, the
33 temperatures in the 16th century were generally lower than those recorded today (1951–2000), particularly in the case
34 of the reconstruction based on the fir chronology (December–March). Anomalies, however, both positive and negative,
35 were usually of less than one standard deviation from the long-term mean. On the other hand, in northern Poland, the
36 February–March temperatures in the 16th century were, on average, comparable to those of the present. Most available
37 temperature reconstructions for Poland reveal cooling over the last few decades of the 16th century, particularly during
38 the winter half-year. The climate in the 16th century was more continental than it is today.

39

40 SIGNIFICANCE STATEMENT

41 The paper presents an updated comprehensive analysis of Poland’s climate that is the first to address the 16th century
42 using a multiproxy approach (mainly documentary evidence and dendrochronological data). Newly collected historical
43 sources and dendrochronological data were used to reconstruct five updated series of mean air temperature: decadal
44 winter and summer means based on documentary evidence, as well as annual means for winter and for the late winter–
45 early spring period derived from dendrochronological data.

46 **KEYWORDS:** Climate variability and change; 16th century; Documentary evidence; Historical
47 climatology; Dendrochronological data; Climate reconstructions

48 1. Introduction

49 This paper is a continuation of the work of an interdisciplinary team of researchers who aim to
50 present the current state of knowledge about the climate of the last millennium in Poland. We have
51 already published an article presenting the variability and changes in climate during the medieval
52 period (1001–1500) (Przybylak et al., 2023). In the present article, we present the current state of
53 knowledge about the climate of Poland limited to the 16th century because, according to our earlier
54 studies, that century is significantly distinguished by its variability of weather and climatic
55 conditions, having been greater than other, earlier and later centuries (e.g., Przybylak et al., 2005;

56 Przybylak, 2011, 2016). This variability likely also motivated other European researchers who
57 studied in detail the climate changes of the 16th century in Europe as part of a special issue
58 published in the journal *Climatic Change* (1999). Another motivating factor was that in the 16th
59 century (particularly around the middle part), many parts of Europe underwent a significant climate
60 change (from warm/dry to cold/wet conditions) (e.g., Bradley and Jones, 1993 and references
61 therein; Brázdil, 1994; Pfister and Brázdil, 1999; Engelen et al., 2001; Glaser, 2001; Bradley et al.,
62 2003; Luterbacher et al., 2004, 2016; Xoplaki et al., 2005; Brázdil et al., 2010; Esper et al., 2016
63 ~~Luterbacher et al., 2016~~). The mid-16th century is therefore most often accepted by the international
64 community as the beginning of the Little Ice Age (LIA) (Grove, 1988; Hughes and Diaz, 1994;
65 White et al., 2018, and references therein). However, as is often the case, evidence of the LIA's
66 onset is not always clear and unambiguous everywhere. The scope of the beginning of the LIA
67 varies significantly; first of all, for many places in Europe (and around the world) it is placed earlier
68 than the mid-16th century mentioned here (for details, see, e.g., Lamb, 1977, 1984; Grove, 1988,
69 2001; Bradley and Jones, 1993; Pfister and Brázdil, 1999; Brázdil et al., 2005).

70 To date, the climate of Poland in the 16th century has never been analysed in detail as a
71 separate study, apart from in a recent analysis regarding floods (Ghazi et al., 2023). A small amount
72 of data from Poland was used in a cycle of journal papers that analysed the climate in Europe (see
73 Glaser et al., 1999; Pfister et al., 1999a). In those papers, the only data used were daily data from
74 Kraków (Eng. Cracow) based on Biem's weather records and encompassing only 17 years within
75 the period 1502–40. Moreover, the reconstruction of the 16th-century European climate based on
76 documentary evidence did not include the area of Poland (see Pfister et al., 1999b). However,
77 several studies have used this kind of proxy data to analyse weather or climate in Poland in short
78 periods (e.g., Bokwa and Limanówka, 2000; Bokwa et al., 2001; Limanówka, 2001; Nowosad and
79 Oliński, 2000; Oliński, 2022; Związek et al., 2022). Most describe climatic conditions in general
80 terms, typically based on the frequency of seasons—most often winter and summer—characterised
81 by extreme weather such as cold, heat, dryness, or wetness. The only more detailed analysis
82 employing such proxy data was that of Limanówka (2001), who undertook a qualitative
83 reconstruction of air temperature and precipitation for Kraków for three short periods: 1502–07,
84 1527–31 and 1535–40.

85 Some information about weather and climate in Poland in the 16th century is also available in
86 papers analysing more extended periods covering a few centuries (e.g., Maruszczak, 1988, 1991;

87 Sadowski, 1991; Wójcik et al., 2000; Przybylak et al., 2001, 2004, 2005, 2020, 2025; Majorowicz
88 et al., 2004; Szychowska-Krapiec, 2010; Zielski et al., 2010; Przybylak, 2011, 2016; Koprowski et
89 al., 2012; Hernández-Almeida et al., 2015, 2017; Balanzategui et al., 2018; Opała et al., 2021;
90 Ghazi et al., 2025). Most reconstructions concern air temperature during the winter half-year, and
91 significantly less information about summer temperature is available. The opposite case holds for
92 other parts of Europe, where most reconstructions address the warm half-year (for details, see, e.g.,
93 Bradley and Jones, 1993; Moberg et al., 2005; Ljungqvist, 2010; Luterbacher et al., 2016). This
94 fact means that reconstructions from Poland can significantly enhance our knowledge of the
95 European climate, especially its central part, particularly in light of the finding of Luterbacher et
96 al. (2010) that winter temperatures in Poland correlate closely with those in almost all of Europe.
97 Regarding precipitation in Poland in the 16th century, little is known. The number of precipitation
98 reconstructions is limited, generally comprising descriptive information or, at best, indices
99 (Maruszczak, 1991; Przybylak et al., 2004; Przybylak, 2011, 2016). The only exception is the
100 aforementioned quantitative precipitation reconstruction for Kraków (Limanówka, 2001).

101 New historical sources, together with dendrochronological data collected under the NCN
102 research project entitled *The occurrence of extreme weather, climate and water events in Poland*
103 *from the 11th to 18th centuries in the light of multiproxy data*, enable a new analysis of the weather
104 and climate changes in Poland in the 16th century
105 (<https://extremeweather.umk.pl/pages/funding/?lang=en>). The collected multiproxy data were
106 used to develop new reconstructions of mean air temperature in late winter and early spring, with
107 a yearly resolution (dendrochronological data), and 10-year means of winter (DJF) and summer
108 (JJA) air temperatures (documentary evidence). On the other hand, the documentary evidence
109 allowed for indexing thermal and precipitation conditions for the remaining seasons, i.e., spring
110 and autumn.

111 In this paper, we present an updated comprehensive analysis that is the first to address Poland's
112 climate in the 16th century using a multiproxy approach (mainly documentary evidence and
113 dendrochronological data). The new knowledge presented here is more reliable and accurate than
114 that which previously existed (Przybylak et al., 2005; Przybylak, 2011, 2016), which should enable
115 us to confirm whether, in Poland as in most European regions, a climatic deterioration occurred in
116 the second half of the century. Another advantage we expect is an improved understanding of the

117 potential causes of climate variability in that century, particularly those underlying climate
118 deterioration.

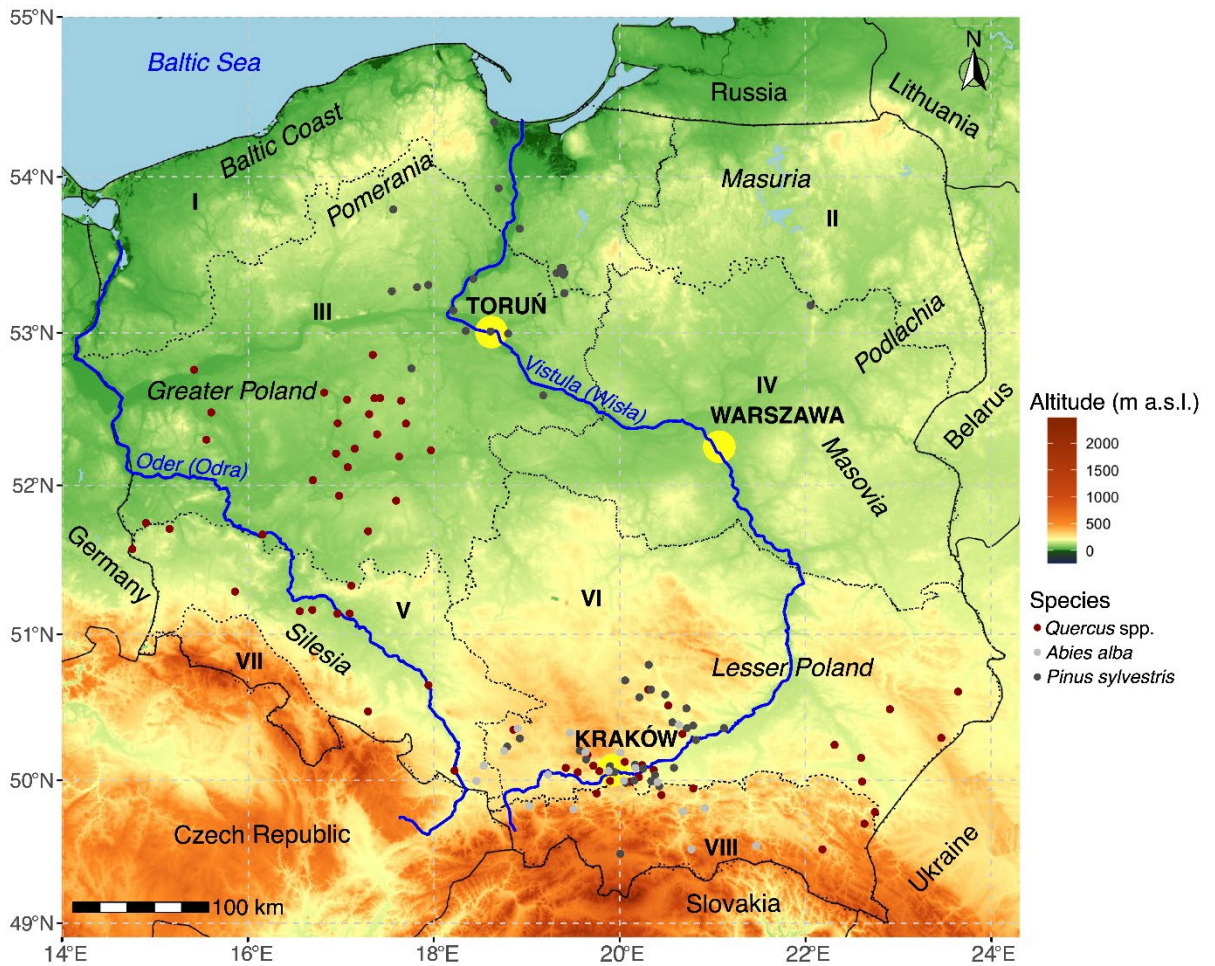
119

120 2. Area, data and methods

121 2.1. Area

122 In the 16th century, Poland (then known as the Polish-Lithuanian Commonwealth) was one of the
123 largest countries in Europe, alongside Russia and the Ottoman Empire, with an area of
124 approximately 800,000 to 815,000 square kilometres and a population of seven to eight million
125 (Wyczański, 1965; Topolski, 2015). Poland was a considerable political, military and economic
126 power at that time. It supplied timber and agricultural products to Western Europe (earning it the
127 moniker of “the granary of Europe”). The contemporary area of Poland (Fig. 1), for which we
128 present the analysis, is about one-third the size and covers only the western part of the
129 Commonwealth.

130 Zielony and Kliczkowska (2012) distinguished eight Natural-Forest Provinces in Poland (Fig.
131 1). Figure 1 also presents the locations of dendrochronological sites and the historical regions
132 covered by the available documentary evidence. For historical regions that differ from their modern
133 boundaries, sources written outside contemporary Poland were considered.



134
 135 Fig. 1. Study area with historical and natural-forest regionalisation and location of materials used for research.
 136 Natural-Forest Provinces (Zielony and Kliczkowska, 2012): I – Baltic Coast province, II – Masuria–Podlachia
 137 province, III – Greater Poland–Pomerania province, IV – Masovia–Podlachia province, V – Silesia province, VI
 138 – Lesser Poland province, VII – Sudetia province, VIII – Carpathia province. Dendrochronological sites: blue
 139 dots – pine, brown dots – oak, grey dots – fir. Yellow dots – meteorological stations

140

141 2.2. Data and methods

142 2.2.1. Documentary evidence

143 The article attempts to utilise the widest and most diverse sources possible. Narrative sources
144 predominated, including chronicles, annals, memoirs, diaries, and the like. Sources from two Polish
145 regions, namely Silesia and Pomerania, dominated this group, followed by slightly fewer sources
146 from Lesser Poland. They were most often written in urban environments and monasteries, and
147 less frequently at the courts of rulers. Examples of such urban sources include the chronicles of
148 Christoph Beyer, *Die ältere Danziger Chronik*, and F. Schwarz, *Chronica oder Handbüchlein*
149 *Danziger Geschichte* (both written in Gdańsk), as well as Nicolaus Pol's *Jahrbücher der Stadt*
150 *Breslau*, written in Wrocław, and Wenceslaus Thommendor's *Schweidnitzer Chronik*, written in
151 Świdnica. Examples of monastic chronicles include the chronicles of the Cistercian monasteries in
152 Oliwa and Pelplin in Pomerania, as well as *Catalogus abbatum Saganensium* from the Augustinian
153 monastery in Żagań.

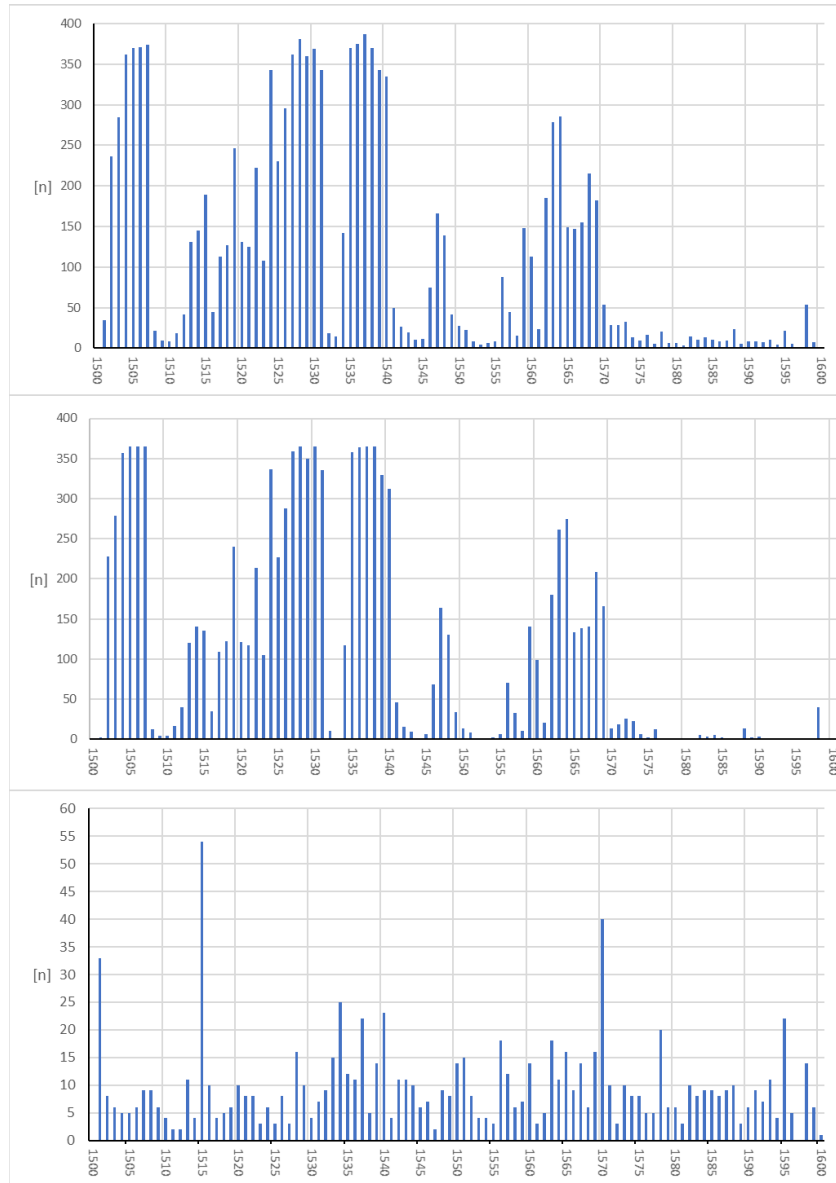
154 The second important group of sources comprises administrative sources produced by
155 rulers, administrators and various offices. These included correspondence requesting the waiving
156 or reduction of taxes due to natural disasters, as well as requests for repairs to buildings damaged
157 by floods, storms and strong winds, along with accounting records documenting such damage.
158 These were published in collections such as the *Acta Tomiciana*, though a significant portion
159 remains (unpublished) in archives and requires archival research to obtain the information.

160 A new type of source for the 16th century is printed multi-year calendars, the oldest of which
161 in Polish collections was published in Ulm in 1499. These reached members of the intellectual
162 elite, becoming an essential contribution to their intellectual work. Due to the nature of the source,
163 calendars precisely determine the date of a weather phenomenon. Determining the location to
164 which a record refers can be problematic, however, especially when the author led an active
165 economic and political life, owned estates scattered across a vast country and travelled to
166 parliaments, regional councils and tribunals held in various cities. Fortunately, for the 16th century,
167 almost all calendars containing meteorological observations were created by professors at the
168 University of Kraków. Consequently, we have the largest number of records and the longest
169 sequences for Kraków. The level of education of the authors of the calendar entries, their daily
170 scientific activities and their interests combine to guarantee a high degree of reliability of weather
171 observations. These sources appear in the form of handwritten supplements in old prints (e.g., BJ
172 Cim. 5521; BJ Cim. 5526; BJ Cim. 5527; BJ Cim. 5528; BJ Incun. 2697). Only a few of them were
173 published: 1) Jan Musceniusz, Jan Krzysztorski, Stanisław Krzysztorski, *Dzienniki z XVI w.*

174 w druku BJ Cim.8421 [Diaries from the 16th century in print BJ Cim.8421], eds. Jacek Partyka
175 and Marian Malicki, Poznań 2009, 2) Mikołaj z Szadka and Marcin Glicjusz z Pilzna, Diariusze
176 profesorów Uniwersytetu Krakowskiego z lat 1555-1591 BJ Cim. 8420 [Diaries of professors at
177 the University of Kraków from the years 1555–91 BJ Cim. 8420], eds. Dawid Machaj and Maciej
178 Zdanek, Kraków 2024.

179 Information was also obtained from later publications (including various 17th- and 18th-
180 century studies, as well as 19th-century monographs) when these were the only sources of
181 information about a weather event. Attempts were made to assess the likely missing source and the
182 reliability of such information.

183 We analysed a total of 11,863 weather records, but the majority (10,906) are daily weather
184 notes produced by professors at the Jagiellonian University (Fig. 2, see also Limanówka, 2001).
185 The others are weather notices that we found in narrative and administrative sources (Table S1,
186 Fig. 2). **Examples are listed in Table S2 and shown in Fig. S1. On the other hand, a list of the**
187 **documentary** sources used is provided in Table S3.



188

189 **Fig. 2. Annual number of weather-related notes and excerpts (n) for Poland available in 16th-century historical**
 190 **sources**

191 Key: upper figure: all weather notices; middle figure: number of weather notices made by professors of the Jagiellonian
 192 University (Limanówka, 2001); lower figure: number of weather notices in narrative and administrative sources

193 Within the study period, the sub-period with the most abundant weather records is 1501–40
 194 (Fig. 2), when the yearly number of weather notes often exceeds 350. Conversely, the final three
 195 decades of the 16th century exhibited the lowest abundance, when the annual number was below
 196 50, except for one year (1598) (Fig. 2). However, notably, when daily weather notes produced by
 197 professors of the Jagiellonian University are removed (Fig. 2c), the number of weather notes is
 198 distributed approximately evenly throughout the century and rarely exceeds 20 per year;

199 nevertheless, three years are particularly abundant in weather notes. These are 1515, 1570 and
200 1501, when the number of weather notes reached 54, 44 and 33, respectively. The number of
201 weather notes was greatest for summer (384 notes), followed by spring (210), winter (207) and
202 autumn (148) (see Table S1).

203 For the entire 16th century, two new sets of thermal and precipitation indices with seasonal
204 resolution were independently created by two of the authors of the present paper (a climatologist
205 and a historian). For this purpose, the information derived from the historical source types
206 presented above was supplemented by previous catalogues (Walawender, 1932; Girguś and
207 Strupczewski, 1965; database of natural disasters: [https://pth.net.pl/projekty/bazy-danych/kleski-](https://pth.net.pl/projekty/bazy-danych/kleski-elementarne/do-1795)
208 [elementarne/do-1795](https://pth.net.pl/projekty/bazy-danych/kleski-elementarne/do-1795), last access: 15 June 2025; Euroclimlist database:
209 https://www.euroclimhist.unibe.ch/datenbanksuche/index_ger.html, last access 14 March 2025,
210 and, finally, on our unpublished database constructed during previous projects). In the event of
211 discrepancies in the assessment of thermal or precipitation conditions, a reanalysis of the weather
212 notes was performed to establish a uniform indexation. The indexation was made using a seven-
213 degree scale, as described by Pfister (1994). He proposed that index values of +3 and -3 indicate
214 air temperature anomalies exceeding 2.0 standard deviations (SD) from the long-term mean, while
215 +2/-2 and +1/-1 correspond to less extreme anomalies of 1.41–2.00 SD and 0.7–1.4 SD,
216 respectively; a value of 0 (> -0.7 SD to <0.7 SD) denotes the average climate of the long-term
217 period or missing data. We slightly modified these SD criteria to account for the specificity of the
218 Polish climate, which differs from that of Switzerland, for which the SD limit values were
219 established by Pfister. For more details on the procedure used, see Przybylak et al. (2023).

220 The updated indices were used to reconstruct 10-year mean winter and summer temperatures
221 for the 16th century, as previously presented by Przybylak (2011). The method employed for this
222 reconstruction is described in Przybylak et al. (2005) and is therefore not repeated here. On the
223 other hand, the strengths and weaknesses of reconstruction based on documentary evidence are
224 discussed by Przybylak et al. (2023) and Brázdil et al. (2005).

225 The climate continentality of Poland was calculated using Gorczyński's index of thermal
226 continentality according to the following formula (Gorczynski, 1920; Kożuchowski and Marciniak,
227 1985):

$$228 \quad K = (1.7 \times A / \sin \varphi) - 20.4$$

229 where K is the continentality index in %, A is the annual temperature amplitude, and φ is the
230 geographical latitude. Annual temperature amplitude was calculated using mean summer and
231 winter temperatures, as only seasonal temperatures were reconstructed for the 16th century. Also,
232 Warsaw's latitude (52.23°N) was used for calculations.

233 A comparative analysis of climatically extreme years, distinguished using historical sources
234 (indices) and dendrochronological data (pointer years), was also undertaken.

235

236 2.2.2. Dendrochronological data

237 The regional tree-ring chronologies employed in this research were developed by Zielski (1997),
238 Krąpiec (1998), Zielski and Krąpiec (2004) and Szychowska-Krąpiec (2010). Wood material was
239 collected from 40 natural forest stands, as well as from historical buildings and archaeological sites
240 (Fig. 1). Tree cores were collected from living trees at around 1.5 m above ground using 5-mm-
241 diameter increment borers, subsequently air-dried and affixed to wooden mounts according to
242 standard dendrochronological techniques (Cook and Kairiukstis, 1990). For historic structures,
243 samples were obtained as either 15-mm-diameter cores or cross-sectional discs. Measurement
244 paths were prepared along two or three radii of each core. Annual ring widths were measured with
245 a precision of 0.01 mm. All dated series were examined for potential measurement inaccuracies
246 and missing rings using the COFECHA program (Holmes, 1983). Subsequently, mean ring-width
247 series from both living trees and historical timbers were merged to construct a single regional
248 chronology.

249 To eliminate age-related growth trends from the raw ring-width data, the approach outlined
250 by Melvin and Briffa (2008) was implemented using the RCSigFree 45_v2b software (Cook et al.,
251 2014). Variance stabilisation was achieved through an Rbar-weighted adjustment that accounted
252 for fluctuations in sample depth (Osborn et al., 1997; Frank et al., 2007). A robust bi-weight mean
253 was then applied to produce the final standardised chronology (Cook, 1985; Cook and Kairiukstis,
254 1990).

255 The running Rbar and Expressed Population Signal (EPS) statistics were calculated using
256 21-year moving windows with a 10-year step. These parameters served to evaluate the coherence
257 and temporal consistency of the common signal among individual tree-ring series, as well as to
258 define the reliable temporal extent of the chronology used for climate reconstruction. Rbar
259 quantifies the proportion of variance shared among individual series, with higher values reflecting

260 stronger common variability (Briffa, 1995). EPS estimates how effectively a finite sample
 261 represents an idealised infinite population (Wigley et al., 1984). Periods with EPS values exceeding
 262 0.85 were considered to exhibit a sufficiently strong common signal in ring-width variability (Table
 263 1).

264 Long-term records of mean monthly air temperature and monthly precipitation from the
 265 Kraków and Toruń meteorological stations were used to assess the climatic sensitivity of the
 266 developed tree-ring chronologies (Fig. 1), applying the methodology described by Fritts (1976).
 267 Once the most robust and temporally stable relationships between ring width and climate variables
 268 were identified, a linear regression-based transfer function was constructed, with the tree-ring
 269 chronology serving as the predictor. The robustness of the regression model was evaluated through
 270 calibration and verification procedures conducted over different time intervals, depending on the
 271 overlap between climatic observations and the tree-ring record (Table 1). All analyses were
 272 conducted in the R environment (R Core Team, 2022) utilising the dplR package (Bunn, 2008) and
 273 the treeclim package (Zang and Biondi, 2015).

274

275 **Table 1.** Statistics overview of chronology and climate reconstructions (after Przybylak et al., 2023)

Chronology	Time span	Number of samples	Eps	snr	Reconstructed parameter	Calibration Period	Calibration statistics	Verification period	Verification statistics			Model for the whole period
									RE=	CE=	prediction RMSE=	
Scots pine. Kuyavia-Pomerania	1168–2015	285	0.966	28.755	Feb–Mar temperature	1871–1943	r=0.477, p<0.05	1944–2015	RE= 0.159	CE= 0.133	prediction RMSE= 0.153	0.45, p<0.05
Scots pine. Lesser Poland	1091–2011	285	0.966	28.702	Feb–Mar temperature	1846–1960	r=0.44, p<0.05	1961–2000				0.39, p<0.05
Silver fir. Lesser Poland	1109–2017	484	0.984	61.337	Dec–Mar temperature	1846–1960	r=0.57, p<0.05	1961–2000				0.49, p<0.05

276

277 Moon rings (MR), sometimes referred to as “included sapwood”, represent a reliable proxy
 278 for severe winter temperature conditions and are characteristic features in the wood of European
 279 oak species (*Quercus robur* and *Quercus petraea*). In cross-section, they appear as light, halo-like
 280 bands within the darker heartwood. Wood containing MRs is distinguished by a reduced abundance
 281 or complete absence of tyloses within the vessels, as well as by a diminished concentration of
 282 heartwood extractives (Dujesiefken and Bauch, 1987; Dzbeński and Krutul, 1994). The formation
 283 of moon rings is linked to disruptions in carbohydrate (starch) allocation that interfere with normal
 284 heartwood development (Dujesiefken and Bauch, 1987). Such disturbances are particularly

285 associated with episodes of exceptionally cold winters (Bolychevtsev, 1970; Dujesiefken and
286 Liese, 1986; Krapiec, 1998).

287 Specimens exhibiting moon rings were identified within a dataset comprising
288 approximately 2,500 oak discs and cores derived from Holocene alluvial sediments in southern
289 Poland, archaeological sites, and timber from historical constructions. The presence and extent of
290 MR zones were examined on prepared transverse surfaces using a binocular magnifier. For each
291 locality, correlation charts were constructed showing tree-ring series for which the MR-affected
292 increments were clearly indicated. Because a portion of the material originated from the basal
293 sections of trunks—where moon ring development is less pronounced (Dujesiefken and Liese,
294 1986; Krapiec, 1999)—the calendar year assigned to the outermost ring of an MR zone may lag
295 the true year of moon ring formation by approximately 2–5 years.

296 Two complementary methods were applied to reconstruct past climate conditions. The first
297 is based on the identification of pointer years across all available chronologies, including both oak
298 and conifer series (Table S4, see also <https://marcin-koprowski.shinyapps.io/app-2/>). The second
299 approach relies on linear regression models developed for pine chronologies from the Kuyavia–
300 Pomeranian region, as well as for pine and oak chronologies from Lesser Poland.

301 Pointer years, as originally defined by Huber and Giertz-Siebenlist (1969), are calendar
302 years in which climatic anomalies cause the majority of trees to form annual rings that are either
303 unusually narrow or unusually wide relative to the preceding year. Such years may result from a
304 range of environmental drivers, encompassing short-lived events (e.g., late spring frosts occurring
305 over a single night) and prolonged climatic stresses, including droughts, harsh winters or extended
306 cold periods (Schweingruber, 1992). Although the specific meteorological causes of individual
307 pointer years are not always straightforward to interpret, their value for dendrochronological dating
308 and climate variability studies is well established. In this study, a year was classified as a pointer
309 year when at least 90% agreement was observed among a minimum of ten tree-ring series.

310 Earlier studies have demonstrated that temperature conditions strongly control tree-ring width
311 variability in Scots pine from both northern Poland (Zielski, 1997; Zielski et al., 2010; Koprowski
312 et al., 2012; Waszak et al., 2021) and southern Poland (Szychowska-Krapiec, 2010). Comparable
313 temperature-driven growth responses have also been documented for fir in southern Poland
314 (Szychowska-Krapiec, 2010). Based on these well-established relationships, temperature was
315 selected as the target variable for the climate reconstruction presented in this study. Following

316 evaluation of the regression models, the earlier segment of the instrumental record was adopted as
317 the calibration period for three study sites (Table 1). The strongest model performance was
318 obtained for fir from Lesser Poland, with correlation coefficients of 0.57 during the calibration
319 interval and 0.49 when considering the full data span. The results of the RE and CE validation
320 statistics indicated satisfactory model reliability, and the root mean square error (RMSE) values
321 were particularly low.

322 3. Results

323 3.1. Documentary evidence

324 As shown in Fig. 2, the number of weather notes collected for Poland in the 16th century, excluding
325 daily weather notes, is evenly distributed over time. However, they vary significantly in number as
326 regards their reporting on weather conditions in the four particular seasons (DJF, MAM, etc.). The
327 greatest differences were noted between summer and other seasons, particularly autumn (see Table
328 S1). Weather notes were slightly more abundant for the first half of the century (493) than the
329 second (464).

330 The available weather notes for Poland for the 16th century allowed 87/38 winters, 39/50
331 springs, 57/78 summers and 41/43 autumns to be indexed in terms of thermal/precipitation
332 conditions. In total, as expected, slightly more seasons were indexed for air temperature (224, i.e.,
333 56%) than for precipitation (209, 52%). Contrary to expectations, however, regarding thermal and
334 precipitation conditions, more seasons were indexed for summer (135) than for winter (125). This
335 is primarily due to the limited amount of information available for winter precipitation conditions
336 (the least of all seasons), which allowed only 38 winters to be indexed, compared to as many as 78
337 summers.

338 Table 2 presents synthesised information on the frequency of seasons in Poland, which
339 experienced either extremely warm and wet conditions or extremely cold and dry conditions in the
340 first and second halves of the 16th century and across the century as a whole. This table shows that
341 extreme events were distributed relatively evenly throughout the 16th century. However, they were
342 slightly more frequent in the first half of the century than in the second. Similarly, extreme events
343 were slightly more frequent for precipitation than for thermal conditions. The most commonly
344 described thermal extremes in the historical sources were extremely cold and very cold winters
345 (indices -3 and -2) and extremely warm and very warm summers (3 and 2). Their frequency reached
346 42.7% and 14.6%, respectively (see Table 2). On the other hand, precipitation extremes were most

347 frequent in summer, with both wet (26.8%) and dry (15.5%) conditions. Thermal and precipitation
 348 extremes were less frequent in autumn.

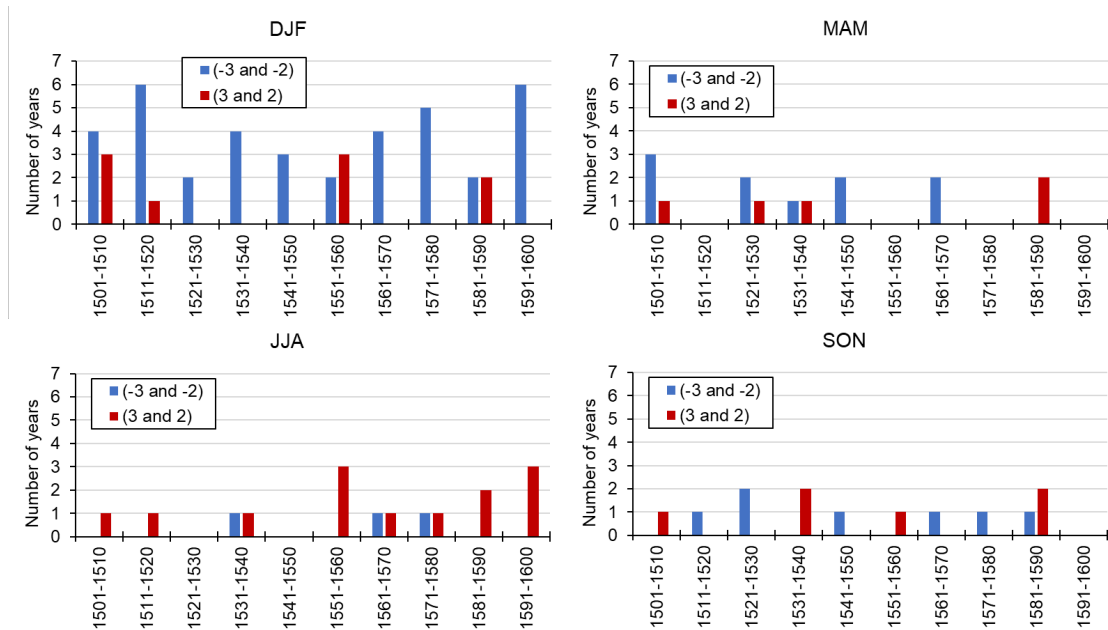
349 **Table 2.** Number of extremely and very warm and cold (T) and wet and dry (P) seasons (DJF, MAM, etc.) in Poland
 350 in the 16th century

Period	Variable	DJF		MAM		JJA		SON		Extreme phenomena	
		-2 & -3	2 & 3	-2 & -3	2 & 3	-2 & -3	2 & 3	-2 & -3	2 & 3	Total	%
1501-1550	T	19	4	8	3	1	3	4	3	45	50.6
	P	7	6	3	10	5	14	1	5	51	52.6
1551-1600	T	19	3	2	2	2	10	3	3	44	49.4
	P	4	3	5	4	10	12	5	3	46	47.4
1501-1600	T	38	7	10	5	3	13	7	6	89	100
	P	11	9	8	14	15	26	6	8	97	100
%	T	42.7	7.9	11.2	5.6	3.4	14.6	7.9	6.7	100.0	
	P	11.3	9.3	8.2	14.4	15.5	26.8	6.2	8.2	100.0	

351

352 Changes in 10-year frequencies of extremely cold and very cold, as well as extremely warm
 353 and very warm seasons in Poland during the 16th century are shown in Fig. 3. The frequency of
 354 occurrence of extremely cold and very cold winters was highest in the decades 1511–20 and 1591–
 355 1600 (6 cases each) and lowest (only 2 cases) in the decades 1521–30, 1551–60 and 1581–90. It is
 356 worth noting, however, that they occurred in each decade, whereas extremely warm and very warm
 357 winters occurred in only four decades, at a lower frequency than that of the mentioned cold
 358 extremes. The opposite relation is noted for summer, when extremely warm and very warm
 359 summers dominate over cold ones (Fig. 3). They were particularly frequent in the second half of
 360 the 16th century (occurring in 10 separate years). As with winters, extremely cold and very cold
 361 springs (10 cases) were clearly more frequent than extremely warm and very warm springs (5) and
 362 were most common in the first half of the 16th century (8 cases, Fig. 3). Both extremely cold and
 363 extremely warm autumns were evenly distributed throughout the study period, but the former were
 364 slightly more frequent.

365

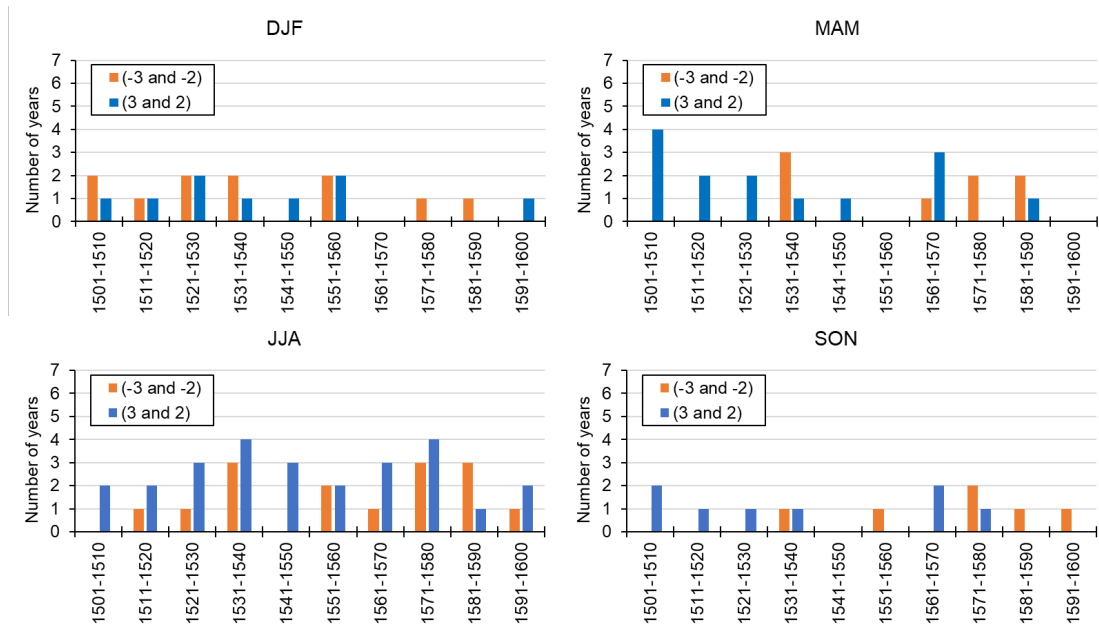


366

367 **Fig. 3.** Decadal number of years frequencies of extreme winters (DJF), springs (MAM), summers (JJA), and
 368 autumns (SON) in 16th-century Poland, categorised as extremely cold and very cold (indices -3 and -2) and extremely
 369 warm and very warm (indices 2 and 3)

370 The analysis of extremely wet/dry and very wet/dry seasons, as shown in Fig. 4, reveals
 371 that they were most abundant in summer and least in autumn. Summer exhibits two maxima in the
 372 occurrence of the 10-year greatest frequencies, for both wet and dry extremes (1531–40 and 1571–
 373 80). In both decades, as many as four extremely wet and very wet summers occurred, and three
 374 extremely dry and very dry summers (Fig. 4). The frequency of such summers was lowest in the
 375 first two decades and the last decade. A large number of extreme seasons was noted for spring,
 376 being even greater than for winter (Fig. 4). Extremely wet and very wet springs were particularly
 377 frequent in the first three decades (8 cases), whereas extremely dry and very dry springs dominated
 378 in the second half of the century. The same pattern of changes in the occurrence of spring extremes
 379 is also evident in autumn extremes (Fig. 4). In turn, the historical sources report that winters were
 380 extremely dry and very dry more frequently than they were extremely wet and very wet. In contrast
 381 to all other seasons, the analysed dry winters were more frequent in the first half of the 16th century
 382 than in the second half.

383



384

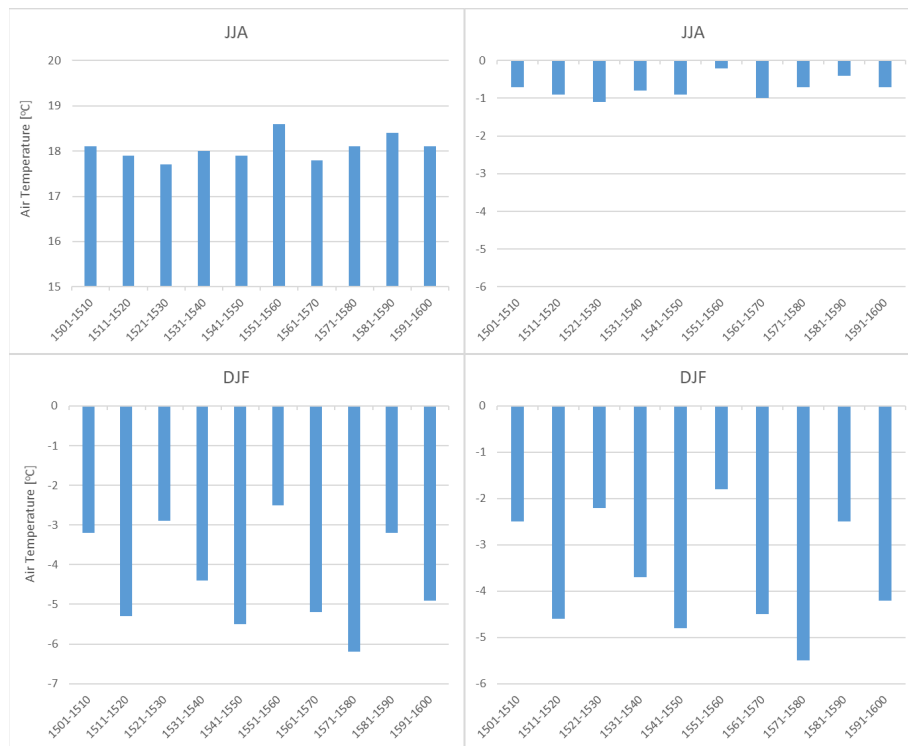
385 **Fig. 4.** Decadal number of years frequencies of extreme winters (DJF), springs (MAM), summers (JJA), and
 386 autumns (SON) in 16th-century Poland, categorised as extremely dry and very dry (indices -3 and -2) and extremely
 387 wet and very wet (indices 3 and 2)

388

389 For extremely cold and very cold winters, less than half (42%) of the information on
 390 humidity is available. The analysis showed that most extremely cold and very cold winters were
 391 either very wet (snowy) (37.5%) or very dry (25%). The remaining winters were slightly wet (25%,
 392 index 1) or normal (12.5%, index 0). The thermal and precipitation relationships for extremely
 393 warm and very warm summers were far less ambiguous. In the 13 such years identified (see Fig.
 394 3), information on their humidity was also available in 11 cases (84.6%). Such extremely hot
 395 summers were almost always accompanied by dry (18.2%) or very dry and extremely dry (72.7%)
 396 summer conditions. Only once (9.1%) was the summer defined as normal.

397 Figure 5 presents an updated version of air temperature reconstructions for Poland for the
 398 16th century, which differs from the earlier version presented by Przybylak et al. (2005) and
 399 Przybylak (2011). The significant improvement in quality and reliability of the present
 400 reconstructions is due to the greater number of historical sources available to us. Analysis shows
 401 that, in Poland, the climate was colder in the 16th century than today (1991–2020), particularly in
 402 winter. On average, winter was 3.6 °C colder, but there was a large range between the warmest
 403 decade (1551–60, anomaly -1.8 °C) and the coldest (1571–80, -5.5 °C). The weather in summer
 404 during the study period was only slightly colder than today, by an average of 0.7 °C. The range of

405 variability of anomalies in mean decadal summer temperatures in relation to present conditions
 406 was also clearly smaller than in winter and ranged between $-0.2\text{ }^{\circ}\text{C}$ (the warmest decade being
 407 1551–60) and $-1.1\text{ }^{\circ}\text{C}$ (the coldest decade being 1521–30). We can therefore conclude that, because
 408 both winter and summer were warmest in the decade 1551–60, it is likely that this decade was also
 409 the warmest in terms of annual values. It is also interesting to compare the temperature averaged
 410 for both the 16th century and the 20th century. Calculations indicate that summers were $0.3\text{ }^{\circ}\text{C}$
 411 warmer in the 16th century than in the 20th century, whereas winters were $2.5\text{ }^{\circ}\text{C}$ colder. The annual
 412 temperature range (summer minus winter) in Poland in the 16th century was significantly greater
 413 (by about $3\text{ }^{\circ}\text{C}$) than it is at present, indicating that climate continentality was also greater.
 414 According to Gorczyński's index of thermal continentality, that difference reached about 6%. The
 415 deterioration of the climate in the last decades of the 16th century is seen only in winter and not in
 416 summer.
 417

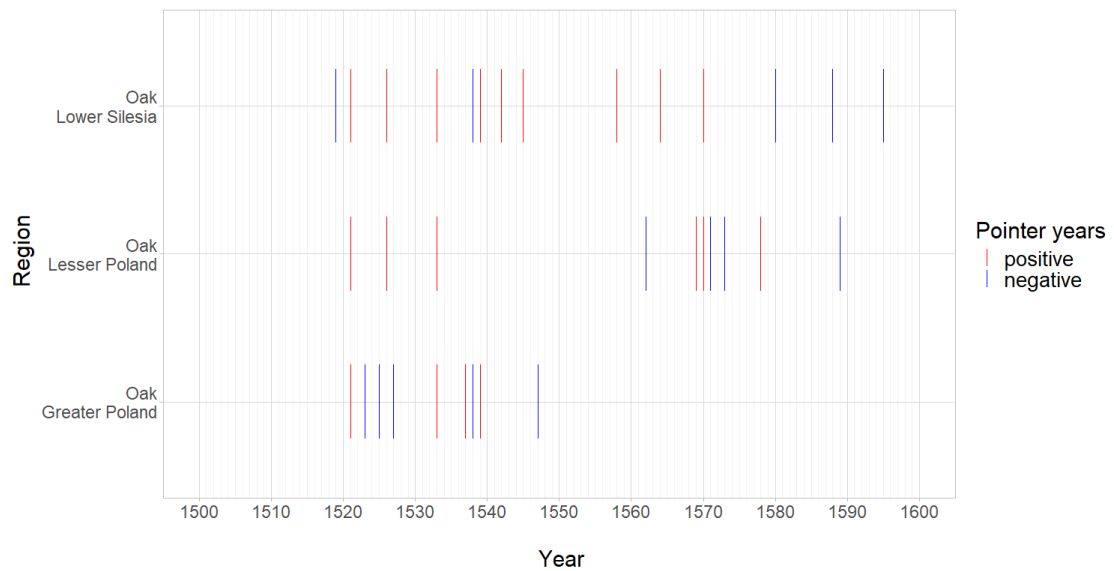


418
 419 **Fig. 5.** (Left panel) Reconstructed 10-year mean winter (DJF) and summer (JJA) air temperatures in Poland during the
 420 16th century; (Right panel) anomalies relative to the 1991–2020 reference period, based on data from Warsaw (Lorenc,
 421 2001, updated)

423 3.2. Dendrochronology

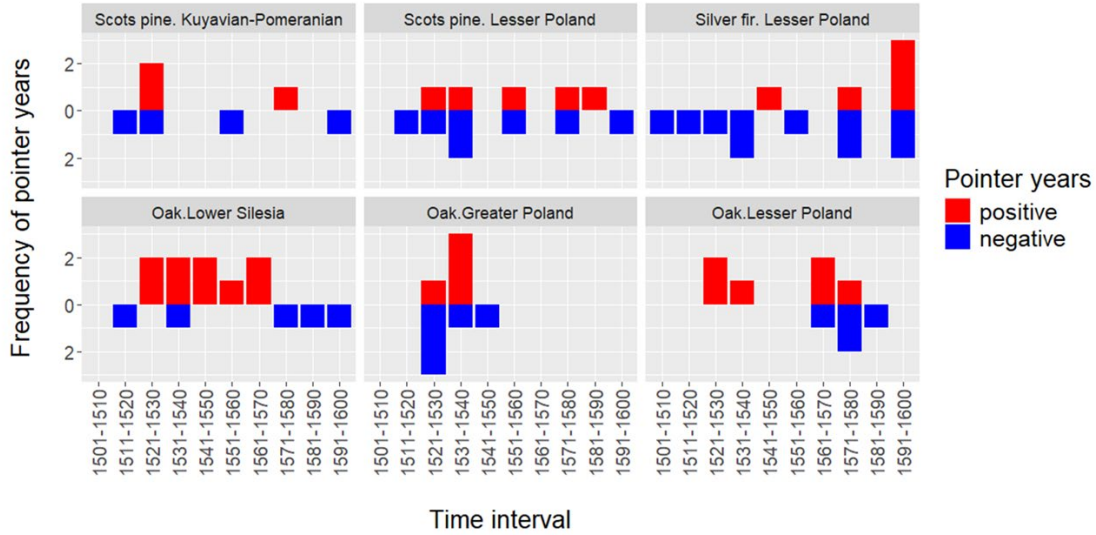
424 3.2.1. Pointer years and moon rings

425 Oak chronologies for Greater Poland, Lower Silesia, and Lesser Poland encompassed the full
426 analysed period from AD 1501 to 1600. Tree-ring sequences from the regional chronologies were
427 employed to determine pointer years in Lesser Poland, Greater Poland, and Lower Silesia (see
428 <https://marcin-koprowski.shinyapps.io/app-2/>, Table S4, and Figs. 6 and 7). During the study
429 period, only two positive pointer years (1521 and 1533) were shared across all three regions.
430 Overall, between 1501 and 1600, 14 pointer years were identified in Lower Silesia, ten in Lesser
431 Poland, and nine in Greater Poland (Figs. 6 and 7).



432

433 **Fig. 6.** Oak pointer years identified in Greater Poland, Lower Silesia, and Lesser Poland, 1501–1600

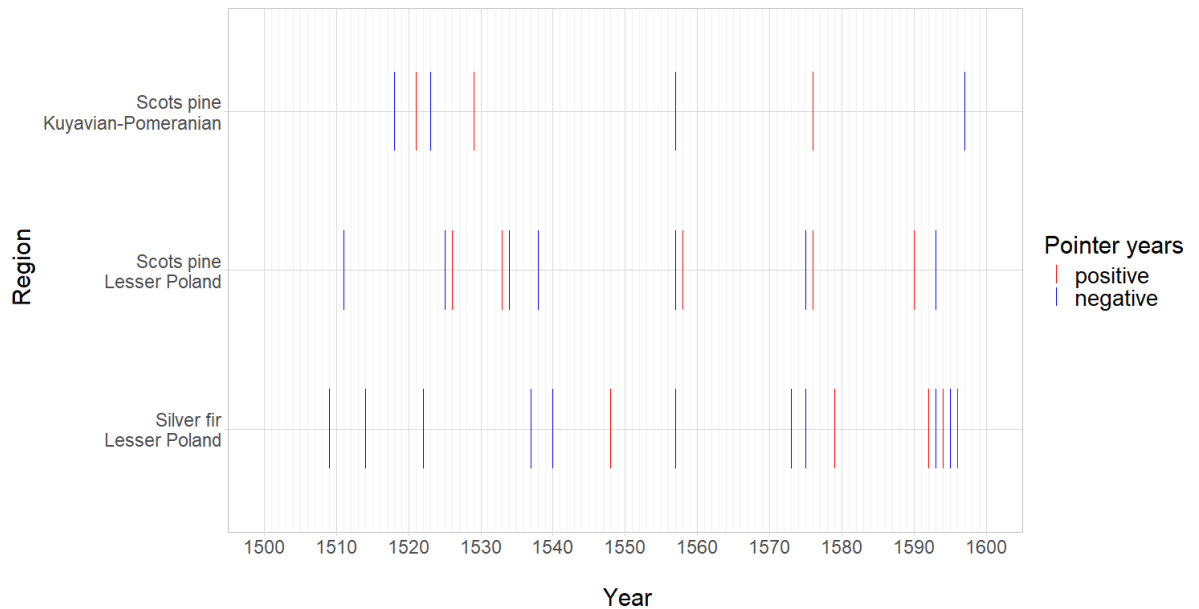


434

435 **Fig. 7.** Decadal frequency of pointer years in Scots pine, silver fir, and oak in Poland, 1501–1600

436

437 Fifteen pointer years were identified in the Lesser Poland silver fir chronology for the
 438 period 1501–1600 (Table S4, Figs. 7 and 8), of which as many as ten were negative pointer years.
 439 This was comparable to Lesser Poland’s Scots pine chronology (1501–1600), where 12 pointer
 440 years were found (Table S4, Figs. 7 and 8). In the case of Scots pine from Kuyavia-Pomerania for
 441 the years 1501–1600, only seven pointer years were identified, of which four are negative (Table
 442 S4, Figs. 7 and 8).



443

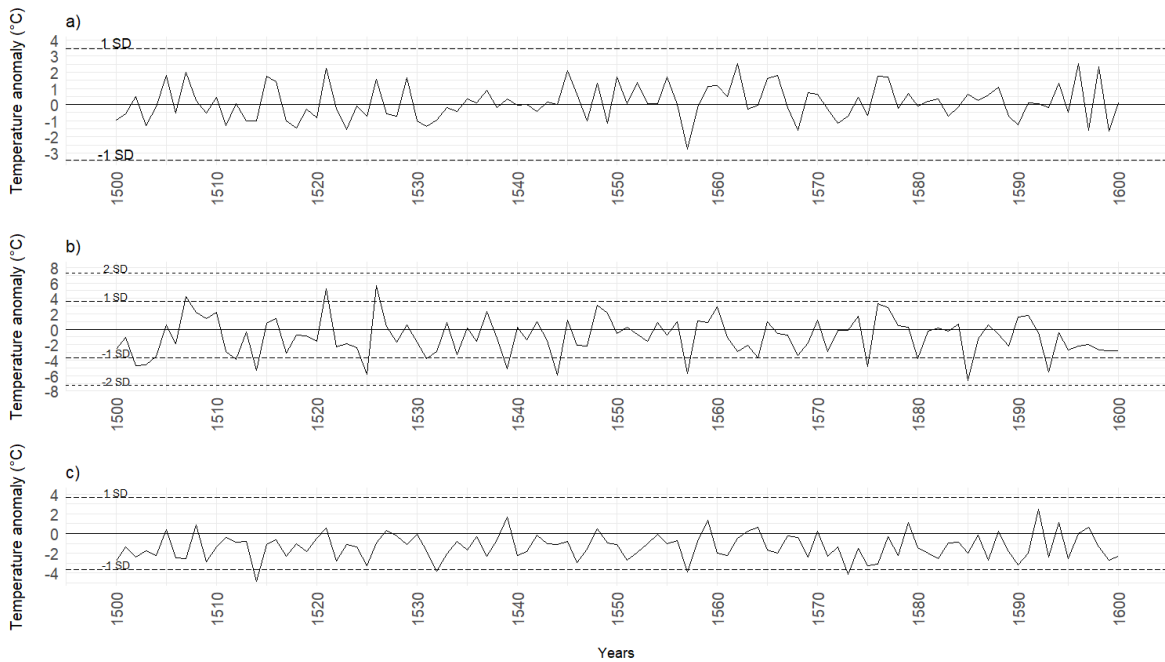
444 **Fig. 8.** Scots pine and silver fir pointer years in Kuyavia-Pomerania and Lesser Poland, 1501–1600

445
446 During the period 1501–1600, MRs were found only for the winter of 1555/56. However,
447 according to historical sources, this winter was very warm in south-western Poland, whereas three
448 coniferous dendrochronologies representing almost the entirety of Poland did not indicate the
449 occurrence of any kind of pointer year, suggesting a rather normal winter.

450 Negative/positive pointer years (roughly representing extremely cold/extremely warm
451 winters, respectively) found in two pine and one fir dendrochronology from Poland, were compared
452 against thermally extreme winters selected from historical sources. The resultant correspondence
453 was very good; 75% (18 cases) of the pointer years distinguished in these dendrochronologies were
454 consistent with the occurrence of extreme winters estimated based on historical sources. For 40%
455 of cases of extreme winters identified based on historical sources, pointer years were not found.
456 Conversely, for 11% of the pointer years, we were unable to find historical weather information.
457 The good correspondence established between dendrochronological pointer years and historically
458 documented extreme winters therefore reasonably warrants the inclusion of dendrochronological
459 data to supplement the database of extreme winters compiled from historical records.

460 3.2.2. Regression model

461 Temperature reconstructions for the winter months based on the three constructed chronologies are
462 presented in Fig. 9 and in a more general form in Fig. 10A–C. For the years AD 1501–1600, the
463 average temperature of February–March (Fig. 9b) was reconstructed using the residual pine
464 chronology, whereas the average temperature of December–March was reconstructed (Fig. 9c)
465 using the residual fir chronology as a predictor. In both reconstructions, the temperatures during
466 the study period were generally lower than those recorded today, particularly in the case of the
467 reconstruction based on the fir chronology (December to March) (Fig. 9c). However, anomalies
468 (both positive and negative) were usually of less than 1 SD from the long-term (1951–2000) mean.
469 On the other hand, in northern Poland, all anomalies were smaller (see Fig. 9a). In this area, also
470 the February–March temperature in the 16th century was, on average, close to the present. The
471 deterioration of the climate in the last decades of the 16th century is most evident in southern
472 Poland, as indicated particularly by the reconstruction of February–March temperatures (Fig. 9b).



473
 474 **Fig. 9.** Reconstructed average air temperatures (°C) in the 16th century: (a) February–March in northern
 475 Poland and (b) February–March in southern Poland, derived from pine-ring widths; (c) December–March in southern
 476 Poland, derived from fir-ring widths. Anomalies are shown relative to the 1951–2000 reference period, with standard
 477 deviations calculated from the same period

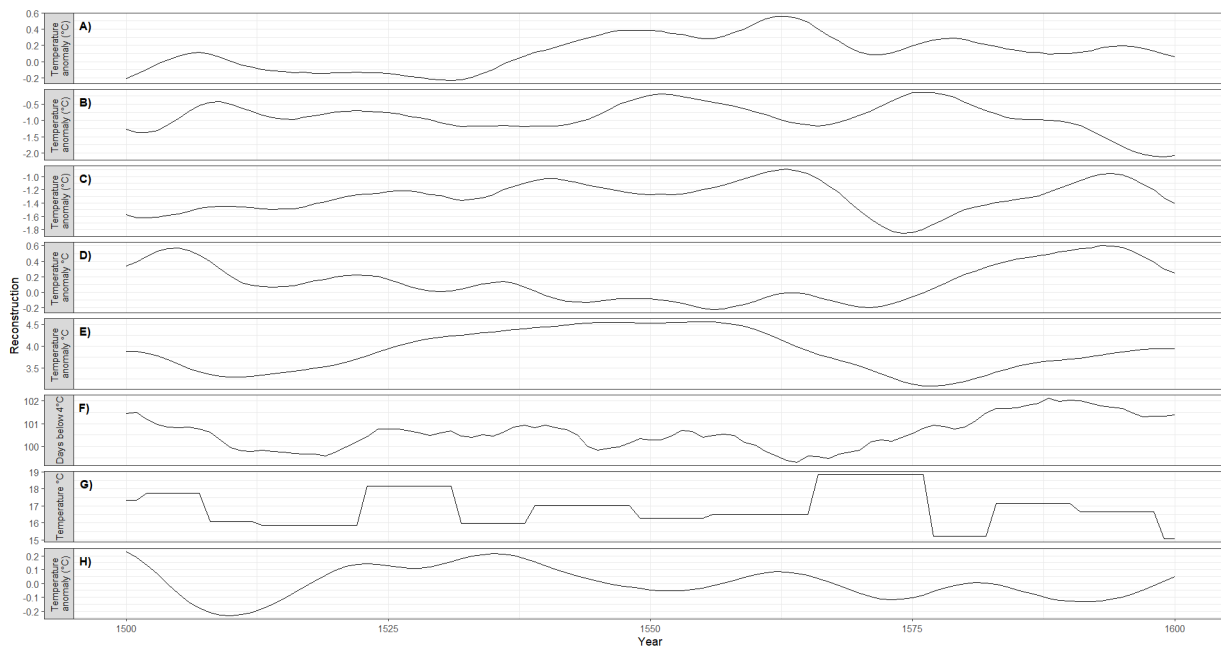
478
 479 4. Summary and discussion
 480 The currently intensifying pace of climate change underscores the urgent need for a precise
 481 understanding of the natural mechanisms controlling climate change across every large and small
 482 region of the Earth, particularly over the past few centuries. Such knowledge allows for a more
 483 reliable assessment of the magnitude of human impact on current and future climate change. These
 484 goals have guided researchers for decades as they reconstruct the climate prior to the period of
 485 instrumental meteorological observations, i.e., usually before 1850 (Brönnimann et al., 2019). The
 486 16th century, as the brief overview presented in the Introduction shows, has been the subject of
 487 research by many authors. There is a significant number of reconstructions, primarily of the most
 488 important climatic element in the temperate and polar zones, which is air temperature (e.g., Bradley
 489 and Jones, 1993; Brázdil, 1994; Engelen et al., 2001; Glaser, 2001; Bradley et al., 2003; Jones and
 490 Mann, 2004; [Luterbacher et al., 2004, 2016](#); [Xoplaki et al., 2005](#); Glaser and Rieman, 2009;
 491 [Ljungqvist, 2010](#); [Lee and Zhang, 2015](#); [Esper et al., 2016](#); [Luterbacher et al., 2016](#); [Pfister, 2018](#)).
 492 However, the available reconstructions presented in these works for small areas (e.g., the Alpine
 493 region, Czech Lands, Scandinavia, Germany, and the Low Countries) or large areas (e.g., above

494 20°N) are most often limited to air temperature during the warm period of the year, mainly the
495 summer. In this article, we present quantitative reconstructions of air temperature for Poland based
496 on both documentary evidence and dendrochronological data for the cold half-year, which
497 significantly enhances our understanding of air temperature changes not only in Poland but also
498 across Europe. As Luterbacher et al. (2010) demonstrated, winter temperatures in Poland are highly
499 and statistically correlated with temperatures across Europe. As Przybylak et al. (2023) concluded,
500 in Poland, winter temperature is the best proxy for estimating the mean annual temperature. Thus,
501 it seems very probable that the winter temperature should also be used ~~to for~~ representing annual
502 temperature in **some parts of Europe, particularly central Europe**, instead of the more usual use of
503 summer temperature for this purpose (see Ljungqvist, 2010).

504 In this paper, we present, for the first time, five new reconstructions of air temperature
505 (Figs. 5 and 9), two based on documentary evidence (for winter and summer) and three based on
506 dendrochronological data (for the cold half-year). As we mentioned in the introduction, one of our
507 primary objectives was to determine whether the 16th-century climate deterioration also occurred
508 in Poland, as it did in many European regions. Analysis of these reconstructions reveals a decrease
509 in winter temperature, particularly in the last three to four decades in southern Poland (see Figs. 9
510 and 10) and throughout Poland (Fig. 5). On the other hand, in the Kuyavia-Pomerania region
511 (northern Poland), this change of temperature is less marked (Fig. 9a, Fig. 10A). This finding is
512 nonetheless in good correspondence with the spatial distribution of air temperature anomalies
513 relative to the 1951–2000 mean presented in Fig. S2. Additionally, there is no evidence to suggest
514 that a marked decrease in summer temperatures occurred in Poland (Fig. 5). **This conclusion is in
515 line with results presented for summer for the entire Europe by Luterbacher et al. (2004).**

516 Let us check other available temperature reconstructions for Poland for this period based
517 on biological or chemical proxies (Fig. 10). Chrysophyte-based reconstruction of the number of
518 days below 4 °C (Hernández-Almeida et al., 2015), representing the cold-half-year temperature,
519 shows clearly that the lowest values occurred in the final two decades (Fig. 10F). Also, Nov–Apr
520 temperature in northern Poland reconstructed based on dendrochronological data (after
521 Balanzategui et al., 2018) confirms this cooling, although here the deterioration of climate started
522 a little earlier, being most intense at the end of the 1570s (see Fig. 10E). It must be noted, however,
523 that temperature here was very high in the period 1530–60, and after that dropped sharply until the
524 late 1570s by about 1.3 °C. Relatively cold temperatures were also observed in the first two decades

525 of the 16th century, as noted in our new reconstructions (see Fig. 9a, c). For the warm half-year, we
 526 have only two reconstructions available, for August (Fig. 10G) and the spring–summer period (Fig.
 527 10H). In August, the temperature in the entire 16th century fluctuated around 17 °C. However, some
 528 signs of cooling are observed in the late 1570s and at the end of the century. Slightly smaller but
 529 longer cooling periods are observed in the first half of the 16th century, mainly in the second
 530 decade. The mean temperature for spring and summer is clearly lower in the second half of the
 531 16th century, although the strongest (but short-term) cooling occurred around the 1510s (see Fig.
 532 10H). We conclude that most of the presented temperature reconstruction reveals a cooling trend
 533 in Poland over the last few decades of the 16th century, particularly in the winter half-year. A
 534 slightly smaller cooling than at the end of the 16th century also occurred in its second decade,
 535 whereas evidently the warmest period was in the middle of that century. This is in good agreement
 536 with reconstructions based on documentary evidence (Fig. 5), which indicate that the warmest
 537 decade was 1551–60, for both winter and summer.



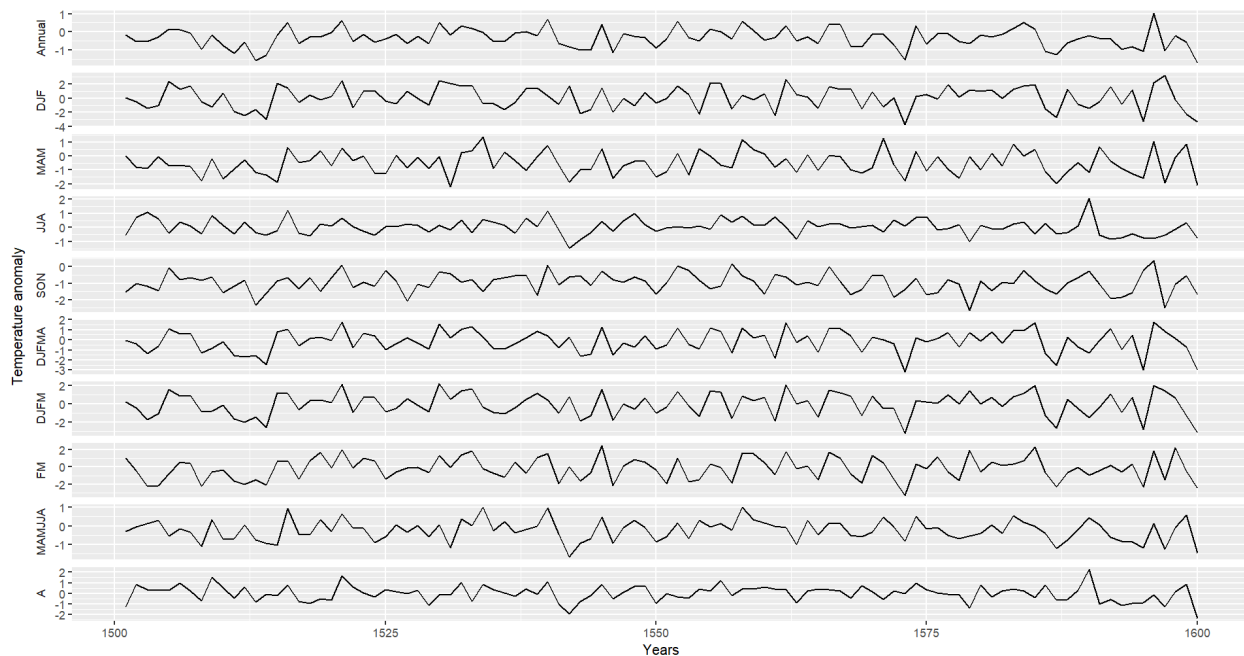
538
 539
 540 **Fig. 10.** Reconstruction of 16th-century air temperatures in Poland using moving-window analysis: Panels A–E depict
 541 temperature anomalies calculated with a Gaussian 20-year moving window for the specified periods and region: A)
 542 Feb–Mar for Kuyavia-Pomerania; B) Feb–Mar for Lesser Poland; C) Dec–Mar for Lesser Poland; D) Feb–Mar for
 543 Kuyavia-Pomerania (modified after Koprowski et al., 2012); E) Nov–Apr for northern Poland (modified after
 544 Balanzategui et al. 2018). F) chrysophyte-based reconstruction of the number of days below 4 °C (Hernández-Almeida
 545 et al., 2015). G) chironomid-based reconstruction of August temperature (Hernández-Almeida et al., 2017). H) a

546 Gaussian 20-year moving window for reconstruction of spring and summer temperature in NE Poland, reconstructed
547 based on the Ca/Ti ratio (modified after Zander et al., 2024). Temperature anomalies are expressed relative to the
548 1951–2000 reference period

549 Recently, a global monthly palaeo-reanalysis of the modern era 1421–2008 (ModE-RA)
550 was published (Valler et al., 2024). The temperature reconstructions averaged for the Polish area
551 for the 16th century, drawn based on data taken from this palaeoreanalysis, are shown in Fig. 11
552 (entire century) and Fig. S2 (1586–1600). It is possible to roughly assess how well they reconstruct
553 the temperature in Poland by comparing their results against the reconstructions presented in the
554 present paper in Figs. 5 and 10. As shown in Fig. 3 of Valler et al. (2024) for Poland for the 16th
555 century, they used only limited documentary evidence for climate reconstruction, primarily from
556 areas neighbouring Poland, which means that the data presented for Poland are obtained from
557 model simulations. Additionally, all reconstructions presented in Fig. 10 represent only a portion
558 of Poland. Only documentary-based reconstructions (Fig. 5) represent the entire area of Poland.
559 Therefore, comparisons of air temperature values may be burdened with a significant error, due to
560 their large spatial variation in Poland, e.g., up to about 2 °C/4 °C in annual/winter mean (1951–
561 2018), respectively, between the north-east and south-west parts of Poland (see Fig. 11.1, Ustrnul
562 et al., 2021). **One of the most important reasons for this variability is the increasing
563 continentalization of the climate in Poland, which is progressing from west to east (Kozuchowski
564 and Marciniak, 1985) and is caused by the decreasing influence of oceanic masses flowing
565 eastwards from the Atlantic, particularly in winter. The influence of the Baltic Sea on the climate
566 of Poland extends only several dozen kilometres inland, mainly along the coast in north-western
567 Poland. The mentioned maritime air masses bring warming to Poland in winter and cooling in
568 summer.** It seems, however, that the course of air temperature changes in the 16th century can be
569 compared without any significant error, as the temperatures of Polish regions are strongly
570 intercorrelated (Przybylak et al., 2014; Ustrnul et al., 2021; Ptak et al., 2025). Analysis of results
571 shown in Figs 5, 10 and 11 confirmed good coherence between the presented changes in air
572 temperature reconstructions for Poland during the 16th century. Reconstructions based on ModE-
573 RA data also revealed two main cooling periods: one around 1510 and a second, more important,
574 in the last 25–30 years, but particularly in the last 15 years of the century (Fig. 11, Fig. S2). For
575 example, the average temperature during the period 1586–1600 was approximately 0.5 °C lower
576 than the average for the entire 16th century during winter (DJF) and the winter-to-early-spring
577 periods (DJFM and DJFMA). A slightly smaller difference than in the mentioned periods occurred

578 in the FM period (-0.36 °C), whereas the smallest difference of all analysed periods occurred in
 579 autumn (SON), being of only -0.16 °C (Fig. 11). Note, however, that the mid-16th-century warm
 580 phase identified in the majority of reconstructions presented in Figs. 5 and 10 is not seen in the
 581 data taken from the ModE-RA (Fig. 11). Furthermore, at this time, almost the same degree of
 582 cooling occurred as in the late 16th century, in particular in the 1540s. However, we must note that
 583 the cooling in this decade is also evident in reconstructions based on documentary evidence,
 584 particularly in winter (Fig. 5).

585



586

587 Fig. 11. Reconstruction of air temperature in Poland in the 16th century according to ModE-RA data (Valler et al.
 588 2024) for different periods of the year, including periods for which temperature reconstructions exist, constructed based
 589 on different multiproxy data (see Fig. 10). Temperature anomalies are shown in relation to the 1961–90 reference
 590 period, which for Poland well represents the entire 20th century.

591

592 The significant temperature decrease in the last decades of the 16th century in Poland is
 593 consistent with many temperature reconstructions for various areas of the globe, e.g. Central
 594 Europe (e.g., Pfister and Brázdil, 1999; Glaser and Riemann, 2009; Brázdil et al., 2010;
 595 Dobrovolný et al., 2010; Niedźwiedz et al., 2015) and the whole of Europe (e.g., Guiot, 1992;
 596 Bradley and Jones, 1993; Luterbacher et al., 2004, 2016; Brázdil et al., 2005 [for a review]; **Xoplaki**
 597 **et al., 2005**; Esper et al., 2016), Asia and North America (Bradley and Jones, 1993; Esper et al.,

598 2016) and, finally, the Northern Hemisphere (e.g., Bradley and Jones, 1993; Jones et al., 1998,
599 2001; Mann et al., 1999; Crowley and Lowery, 2000; Briffa et al., 2001; Bradley et al., 2003; Jones
600 and Mann, 2004; Moberg et al., 2005; Mann et al., 2008, 2009; Ljungqvist, 2010; Lee and Zhang,
601 2015).

602 It is worth checking whether the same consistency among reconstructions applies to the
603 beginning of the 16th century (the clear cold phase) and the period around the middle of the century
604 (the warming period). Accordingly, a review of the results of available reconstructions (e.g.,
605 Bradley and Jones, 1993; Luterbacher et al., 2004; Brázdil et al., 2005, 2010; Xoplaki et al., 2005;
606 Niedźwiedź et al., 2015) shows that, in the first five to seven decades of the 16th century, the course
607 of temperature fluctuations in Poland very often differs from that in other areas of the globe.
608 However, the occurrence of a cold phase during the first two decades of the 16th century agrees
609 with, for example, the course of average temperature for some areas of Europe, e.g. Central Europe
610 (average from Switzerland, southern Germany and the Czech Republic, see Fig. 7 in Pfister and
611 Brázdil, 1999); North America (see Fig. 6 in Bradley and Jones, 1993), including the Canadian
612 Arctic (Fig. 2 in Bradley and Jones, 1993); or JFMA Stockholm temperature (see Fig. 3 in Brázdil
613 et al., 2010) and summer (JJA) temperature in Scandinavia reconstructed by Büntgen et al. (2011).
614 However, in turn, there is no agreement for the western part of Europe (De Bilt series, Brázdil et
615 al., 2005), Europe as a whole, western Russia, China, the mean for the Northern Hemisphere, and
616 many other regions, as shown by Bradley and Jones (1993). But the newest air temperature
617 reconstructions of the extra-tropical Northern Hemisphere (30–90°N) (see Fig. 3 in Ljungqvist,
618 2010) or of the entire Northern Hemisphere (see Fig. 14.2 in Lee and Zhang, 2015) clearly show
619 both the cooling at the beginning of the 16th century and the warm phase in the middle of this
620 century. A similar trend of averaged annual temperatures for both the Northern and Southern
621 Hemispheres, as well as for the entire Earth, is also observed in Fig. 5 presented by Jones and
622 Bradley (2004). **On the other hand, reconstructions of seasonal temperatures for Europe
623 (Luterbacher et al., 2004; Xoplaki et al., 2005) reveal cooling at the beginning of the 16th century,
624 whereas mid-century warming occurred only in summer.**

625 Thus, we can say that changes in air temperature in Poland during the 16th century were
626 consistent not only on a regional scale, but also on a large (and even hemispheric) scale. The
627 presented results allow us to conclude that, particularly in the late 16th century, cooling was
628 widespread and significant globally. As Pfister and Brázdil (1999) noted, the deterioration of the

629 climate at this time was already registered by Kuhn (1787), who wrote that it caused “alpine
630 glaciers to grow beyond their usual limitations and to extend into cultivated areas”. The most
631 probable reasons for the climate deterioration in Poland over the last decades of the 16th century
632 were the increase in volcanic activity (Toohey and Sigl, 2017) and the decrease in the NAO index
633 (see Fig. 2 in Ortega et al., 2015). The latter, i.e., a negative index of NAO, according to the
634 investigation by Przybylak et al. (2003) for the period 1500–1990, caused severe winters in Poland.

635 5. Conclusions and final remarks

636 The principal results of this paper can be summarised as follows:

- 637 (i) The new presented versions of air temperature reconstructions based on the
638 documentary evidence revealed that the climate of the entirety of Poland in the 16th
639 century was colder than it is today (1991–2020), particularly in winter (Fig. 5). On
640 average, winter was 3.6 °C colder, but there was a large range between the warmest
641 decade (1551–60, anomaly -1.8 °C) and the coldest (1571–80, -5.5 °C). The weather in
642 summer during the study period was only slightly colder than today, on average by
643 0.7 °C.
- 644 (ii) The average 16th-century summer temperature was 0.3 °C warmer, whereas winters
645 were 2.5 °C colder than the average 20th-century value.
- 646 (iii) Dendrochronological reconstructions of the temperature in south-eastern Poland show
647 that the 16th-century climate was generally colder than that occurring today (1951–
648 2000), particularly in the case of the reconstruction based on the fir chronology
649 (December to March). However, anomalies (both positive and negative) are usually of
650 less than 1 SD from the long-term mean (Fig. 9a, b). On the other hand, in northern
651 Poland, the February–March temperatures in the 16th century were, on average,
652 comparable to those of today (Fig. 9c).
- 653 (iv) The deterioration of the climate in the last decades of the 16th century is, as shown in
654 three new dendrochronological reconstructions presented in this study, mainly evident
655 in south-eastern Poland (see Fig. 9 and 10 A-C). Additionally, the reconstruction of
656 winter temperatures based on documentary evidence confirms this finding (Fig. 5).
657 Additionally, most other available temperature reconstructions for Poland (Fig. 10)
658 reveal a cooling in Poland over the last few decades of the 16th century, particularly

659 during the winter half-year, but also in mean spring–summer temperature (Fig. 10H).
660 Reconstructions based on ModE-RA data also revealed a cooling in the last 25–30 years
661 of the century, but particularly in the last 15 years (Fig. 11, Fig. S2). On the other hand,
662 summer temperature reconstructions are ambiguous (Hernández-Almeida et al., 2017;
663 Valler et al., 2024). A reconstruction based on documentary evidence does not indicate
664 a temperature drop in the second half of the 16th century, **except for the decade 1561–**
665 **70** (Fig. 5), whereas a chironomid-based reconstruction of August temperature does
666 (Fig. 10G). Additionally, a global palaeo-reanalysis reveals cooling at this time, **except**
667 **in north-western Poland, in particular along the Baltic coast** (Fig. 11, Fig. S2). **The**
668 **lower accuracy of information on weather conditions in historical sources for the last**
669 **three decades of the 16th century, compared to the earlier period (Fig. 2), may be one**
670 **of the reasons for the uncertainty of summer temperature reconstruction based on the**
671 **documentary evidence.**

672 (v) Temperature changes in Poland during the 16th century, particularly the marked
673 decrease observed in the final decades of the study period, are consistent with many
674 reconstructions for various areas of the globe, such as Central Europe, the whole of
675 Europe, Asia, North America, and even the Northern Hemisphere.

676
677 The new temperature reconstructions based on documentary evidence cover the entire
678 territory of present-day Poland, whereas the dendrochronological reconstructions cover only parts
679 of it, specifically the south and the north. This may be one of the significant reasons for the
680 observed differences, which have been generally confirmed by air temperature reconstructions
681 based on ModE-RA data for this period (see Fig. S2). Another important area of uncertainty is the
682 variation in temperature reconstructions across different periods of the year. The same types of
683 uncertainty also apply to all temperature reconstructions for Poland presented in this paper, which
684 use different proxy data as predictors. Finally, uncertainties are also associated with the
685 reconstruction methods used, as well as inaccuracies inherent in the predictors themselves.

686
687 **Data Availability.** The tree-ring chronologies underlying the findings of this study can be obtained
688 from Elżbieta Szychowska-Krapiec, Marcin Koprowski, and Marek Krapiec upon request. On the

689 other hand, the list of all pointer years is available at: <https://marcin-koprowski.shinyapps.io/app->
690 [2/](#).

691 **Supplement.** The supplementary material related to this article is available online at: xxxx

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693 MKr, ESK; validation: RP, PO, MKo, MKr, ESK; formal analysis: RP, PO, MKo, MKr;
694 investigation: RP, PO, WCh, MKo, MKr, ESK, AP; resources: RP, WCh, PO, MKo, MKr, ESK,
695 AP; data curation: RP, PO, MKo, MKr, ESK, AP; writing – original draft: RP, PO, MKo, WCh;
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698

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1022

1023 Table S1. Number of weather notes/excerpts for Poland available in historical sources describing weather in seasons,
 1024 1501–1600

Decade	DJF	MAM	JJA	SON	Season unknown	Yearly number of excerpts
1501-1510	13	22	33	20	16	91
1511-1520	34	14	31	24	19	108
1521-1530	14	30	36	9	6	69
1531-1540	32	30	55	22	12	143
1541-1550	21	17	35	10	13	82
1551-1560	27	26	28	9	14	91
1561-1570	26	23	58	17	24	138
1571-1580	20	18	32	13	15	81
1581-1590	13	17	31	18	11	75
1591-1600	7	13	45	6	10	79
Total 1501-1600	207	210	384	148	140	957

1025

1026

1027 Table S2. Examples of documentary sources describing the extreme weather and its impact on farming/crops and the
 1028 environment (drought, sea and river ice).

Year	Description	Translation	Source
1556/57	<i>Hoc anno in fine et in principio sequentis hiems fuit valde constans, nives et gelua magna incipiendo a festo fere S. S. Hedvigis usque ad Annuntiationem B. Mariae V. 1557 anni per totum fere Martium usque ad finem glacies fuerunt.</i>	This year, at the end of the year and at the beginning of the following winter, there was very constant snow and frost, beginning almost from the feast of St. Hedwig until the Annunciation of the Blessed Virgin Mary. V. In 1557, there was ice almost throughout March until the end.	Ż e g o t a — Manuscript No. 5358, Library of the Jagiellonian University, Kraków.

1564/65	<i>Zu Breslau und anderswo war abermal ein sehr harter, kalter Winter dass alle schiffreichen Wasser, als der Rhein, Donau, Main, ... und auch die Oder dermassen überfrozen, dass, man in allen Orten mit geladenen Wagen darüber fahren können ... Dieser Kalte langwierige Winter hat angefangen um Martini des vorgehenden Jahres, und hat gawähret bis auf Mathiä, vier ganzer Monat.</i>	In Breslau and elsewhere, there was once again a very harsh, cold winter, so that all navigable waterways, such as the Rhine, Danube, Main, and also the Oder, froze over so completely that one could not drive across them with loaded wagons in any of the places... This cold, long winter began around Martinmas of the previous year and lasted until St. Matthias' Day, four whole months.	Pol N., Jahrbücher der Stadt Breslau. Edidit J. G. B ü s c h i n g. I. — V. Bde. (965—1623). Breslau 1811—1827.
1568/69	<i>Sehr starke Kälte. Man fährt auf dem Eise nach Heia und Lübeck.</i>	Extremely cold. One travels on ice to Hel and Lübeck.	Violet A. F., Neringia oder Geschichte der Danziger Nehrung. Danzig 1864.
1590	<i>Ist ein sehr heisser truckener Sommer gewesen, also, dass auch die Landflüsse, als der Bober, Queiss, Katzbach, Weida, Olau, Lohe, und andere mehr gänzlich ausgetrucknet. Die Oder ist auch so klein worden, dass man sie an allen Orten durchwatten können.</i>	The summer was so hot [and] dry that regional rivers like the Bóbr, the Kwisá, the Kaczawa, the Widawa, the Oława, the Ślęza [Silesia, auth. suppl.] and many others dried up completely. The Odra also became very shallow, so you could cross it anywhere.	Pol N., Jahrbücher der Stadt Breslau. Edidit J. G. B ü s c h i n g. I. — V. Bde. (965—1623). Breslau 1811—1827.
1595	<i>Eodem anno [1595] hyems acris erat et nivida unde resolutio postea ex nimio calore solis lignefactum gelu feria 4ta hebdomadae magna tanta</i>	In the same year [1595], the winter was severe and snowy, from which the resolution later, due to the excessive heat of the sun, the frost on	The Princes Czartoryski Library in Kraków, sygn. IV 1337, Kronika

	<i>damna civibus patrauerat Bidgost. patrauerat hora 9 ante meridiem, talis repentinus casus cives turbarat q[uo]d dato pulso campanae omnes cives cogebantur ad defensionem granariorum frumentis impletarum adesse, t[a]m[e]n in aliquot granarijs damnum cives sunt experti et in sale duraverat haec aqua ad diluculum, habebat semi ulnae spatium adimplendi superioris inundationis anni 1571.</i>	the 4th of the Great Week, caused such great damage to the citizens of Bydgoszcz. It had happened at 9 o'clock in the morning, such a sudden accident disturbed the citizens that when the bell was rung, all the citizens were forced to be present to defend the granaries filled with grain, but in some granaries the citizens experienced damage and this water had remained in the salt until dawn, it had half a cubit space to fill the previous flood of the year 1571.	miasta Bydgoszczy od 966 do 1637 roku.
1598	<i>Im Winter ist ein ungemeiner harter Frost gewesen so daß man in den Kellern sich nicht mehr bergen mögen und hat biß an Mitt-Fasten des folgenden Jahres gedauert da dann das Weichsel Eiß der Brücken einen grossen Schaden zugefüget hat.</i>	In winter, there was an exceptionally harsh frost, so that one could no longer take shelter in the cellars, and this lasted until mid-Lent of the following year, when the Vistula ice caused great damage to the bridges.	Zernecke J. H., Historiae Thoruniensis nafragae tabulae, Thorn 1711.

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1088 *1596. Jahr im Churfürstenhumb Brandenburg, und dazu gehörenden Landen und Herrschafften, von jahr zu Jahr*
1089 *begeben und zugetragen haben. Aus vielen glaubwürdigen Scribenten und Büchern, auch aus bewerten urkunden und*
1090 *vielen alten monumentis, zusammen getragen und beschrieben, Frankfurt a/Oder 1598*
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1312

1313 Table S4. Pointer years of *Abies alba*, *Pinus sylvestris* and *Quercus* spp. in Poland in four historical regions in the

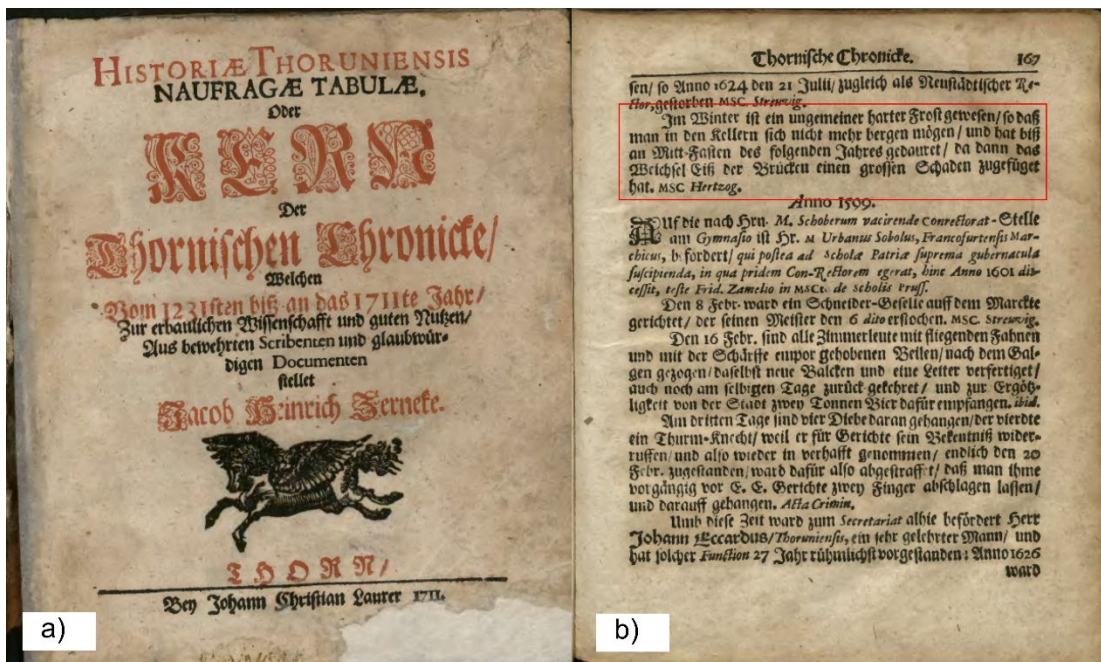
1314 16th century: „-1” – negative; „1” – positive

<i>Species</i>	<i>Quercus</i> spp.	<i>Quercus</i> spp.	<i>Quercus</i> spp.	<i>Abies alba</i>	<i>Pinus sylvestris</i>	<i>Pinus sylvestris</i>
<i>Region</i> <i>Year</i>	Greater Poland	Lower Silesia	Lesser Poland	Lesser Poland	Lesser Poland	Kuyavian- Pomeranian
1501						
1502						
1503						
1504						
1505						
1506						
1507						
1508						
1509				-1		
1510						
1511					-1	
1512						
1513						
1514				-1		
1515						
1516						
1517						
1518						-1
1519		-1				
1520						
1521	1	1	1			1
1522				-1		
1523	-1					-1
1524						
1525	-1				-1	
1526		1	1		1	
1527	-1					
1528						
1529						1
1530						
1531						
1532						
1533	1	1	1		1	

1534					-1	
1535						
1536						
1537	1			-1		
1538	-1	-1			-1	
1539	1	1				
1540				-1		
1541						
1542		1				
1543						
1544						
1545		1				
1546						
1547	-1					
1548				1		
1549						
1550						
1551						
1552						
1553						
1554						
1555						
1556						
1557				-1	-1	-1
1558		1			1	
1559						
1560						
1561						
1562			-1			
1563						
1564		1				
1565						
1566						
1567						
1568						
1569			1			
1570		1	1			
1571			-1			
1572						
1573			-1	-1		
1574						
1575				-1	-1	
1576					1	1
1577						
1578			1			

1579				1		
1580		-1				
1581						
1582						
1583						
1584						
1585						
1586						
1587						
1588		-1				
1589			-1			
1590					1	
1591						
1592				1		
1593				-1	-1	
1594				1		
1595		-1		-1		
1596				1		
1597						-1
1598						
1599						
1600						

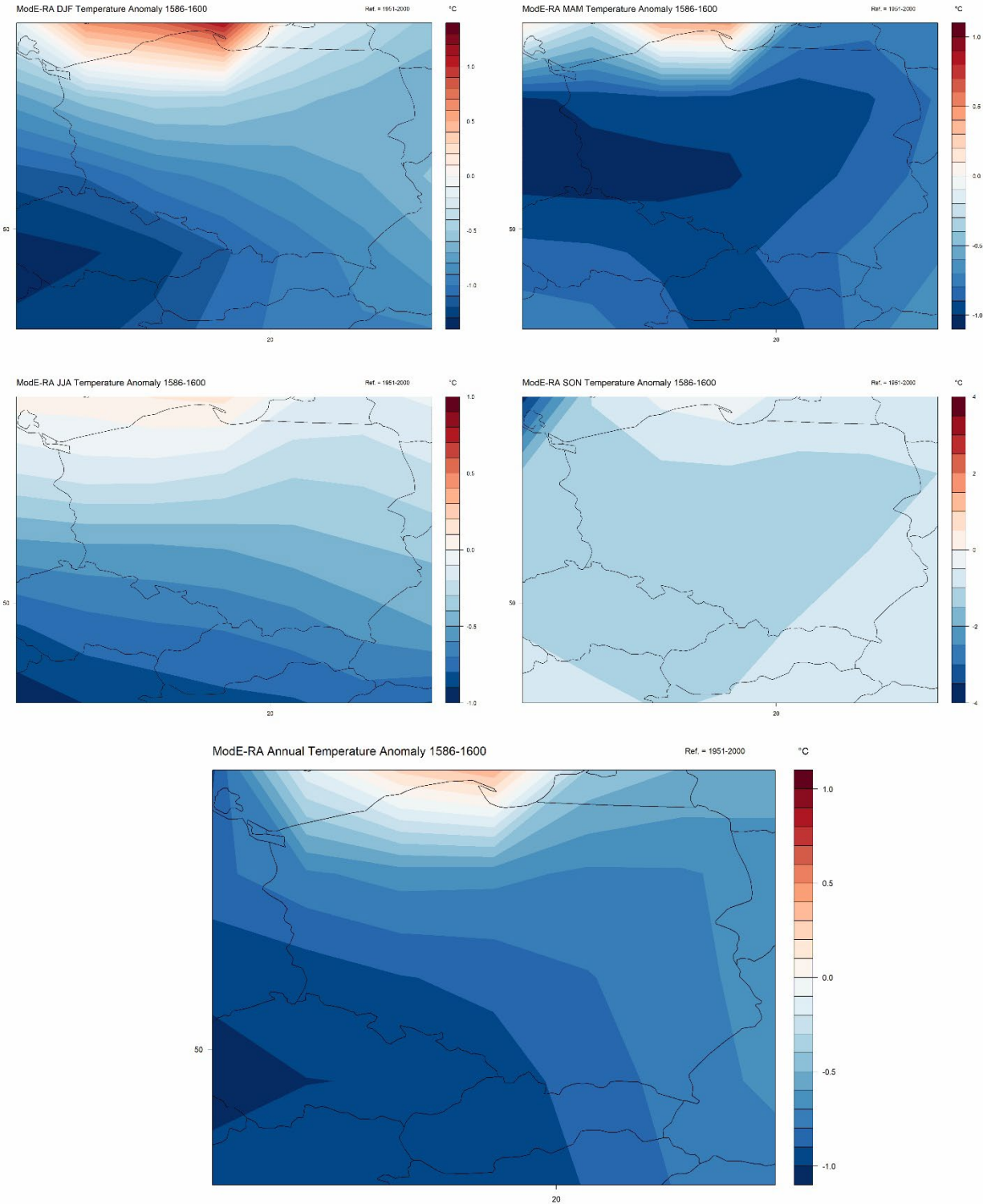
1315



1316

1317 Fig. S1. Example of a documentary source describing harsh weather conditions in winter 1598 in Toruń and their
 1318 influence on the Vistula river (source: Zernecke J. H., *Historiae Thoruniensis naufragae tabulae*, Thorn 1711).

1319 Key: a – title page; b – weather note, see also the last weather note in Table S2 for English translation. Copies taken
1320 from Kujawsko-Pomorska Biblioteka Cyfrowa ([https://kpbc.umk.pl/publication/20358/edition/45669/historiae-](https://kpbc.umk.pl/publication/20358/edition/45669/historiae-thoruniensis-naufrae-tabulae-oder-kern-der-thornischen-chronicke-welchen-vom-1231-sten-bisz-an-das-1711-te-jahr-zur-erbaulichen-wissenschafft-und-guten-nutzen-aus-bewehrten-scribenten-und-glaubwurdigen-documenten-stellet-zernecke-jacob-heinrich-1672-1741?utm_source=chatgpt.com)
1321 [thoruniensis-naufrae-tabulae-oder-kern-der-thornischen-chronicke-welchen-vom-1231-sten-bisz-an-das-1711-te-](https://kpbc.umk.pl/publication/20358/edition/45669/historiae-thoruniensis-naufrae-tabulae-oder-kern-der-thornischen-chronicke-welchen-vom-1231-sten-bisz-an-das-1711-te-jahr-zur-erbaulichen-wissenschafft-und-guten-nutzen-aus-bewehrten-scribenten-und-glaubwurdigen-documenten-stellet-zernecke-jacob-heinrich-1672-1741?utm_source=chatgpt.com)
1322 [jahr-zur-erbaulichen-wissenschafft-und-guten-nutzen-aus-bewehrten-scribenten-und-glaubwurdigen-documenten-](https://kpbc.umk.pl/publication/20358/edition/45669/historiae-thoruniensis-naufrae-tabulae-oder-kern-der-thornischen-chronicke-welchen-vom-1231-sten-bisz-an-das-1711-te-jahr-zur-erbaulichen-wissenschafft-und-guten-nutzen-aus-bewehrten-scribenten-und-glaubwurdigen-documenten-stellet-zernecke-jacob-heinrich-1672-1741?utm_source=chatgpt.com)
1323 [stellet-zernecke-jacob-heinrich-1672-1741?utm_source=chatgpt.com.](https://kpbc.umk.pl/publication/20358/edition/45669/historiae-thoruniensis-naufrae-tabulae-oder-kern-der-thornischen-chronicke-welchen-vom-1231-sten-bisz-an-das-1711-te-jahr-zur-erbaulichen-wissenschafft-und-guten-nutzen-aus-bewehrten-scribenten-und-glaubwurdigen-documenten-stellet-zernecke-jacob-heinrich-1672-1741?utm_source=chatgpt.com))
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 1326 Fig. S2. Spatial distribution of seasonal and annual mean anomalies of air temperature in Poland in the period 1586–
 1327 1600 based on ModE-RA data (after Valler et al., 2024).

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