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Article

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Climate response to the 1257 Samalas eruption revealed by proxy records

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The eruption of Samalas in Indonesia in 1257 ranks among the largest sulfur-rich eruptions of the Common Era with sulfur deposition in ice cores reaching twice the volume of the Tambora eruption in 1815. Sedimentological analyses of deposits confirm the exceptional magnitude (M_c 7, VEI 7) of the Samalas eruption with $\geq 40 \text{ km}^3$ of dense magma expelled and a plinian column estimated to reach 43 km. However, the climatic response to the Samalas event is debated since climate model simulations generally predict a stronger and more prolonged surface air cooling of Northern Hemisphere (NH) summers than inferred from tree-ring based temperature reconstructions. Here, we draw on historical archives, ice-core data and tree-ring records to reconstruct the spatial and temporal climate response to the Samalas eruption. We find that 1258 and 1259 experienced some of the coldest NH summers of the past millennium. However, cooling across the NH was spatially heterogeneous. Western Europe, Siberia and Japan experienced strong cooling, coinciding with warmer-than-average conditions over Alaska and Northern Canada. We suggest that in North America, volcanic radiative forcing was modulated by a positive phase of the El Niño Southern Oscillation. Contemporary records attest to severe famines in England and Japan, but these began prior to the eruption. We conclude that the Samalas eruption aggravated existing crisis, but did not trigger the famines.

Despite the exceptional magnitude of the 1257 Samalas volcanic eruption¹⁻⁴, the apparent lack of strong and widespread cooling in climate proxies, with the exception of Western Europe⁵, has puzzled scientists for almost two decades⁶⁻⁸. This conundrum is emphasized since for some lesser magnitude events, e.g. the 536 “unknown”⁹⁻¹¹, 1600 Huaynaputina¹² and 1815 Tambora^{13,14} eruptions, abundant

61 historical evidence exists for persistent dust veils and widespread NH climatic cooling^{11,15,16}. This
 62 absence of evidence of strong cooling in 1258 even called into question the ability of tree-ring width
 63 proxies to detect the short-term cooling^{8,17-19} associated with the largest volcanic eruptions and the skill
 64 of climate models to predict the magnitude and persistence of volcanic cooling if they do not
 65 incorporate aerosol microphysical modules^{16,20}.

66 **Historical evidence for a strong cooling in 1258**

67 Here, we shed light on the climate forcing associated with the 1257 Samalas eruption through the
 68 analysis of an extensive compilation of mediaeval texts, drawn from the *Monumenta Germaniae*
 69 *Historica*, the *Rerum Britannicarum Medii Aevi Scriptores* and the *Recueil des historiens des Gaules et*
 70 *de la France* (Text S1). A total of 35 narrative sources (Table S1) attest to significant and widespread
 71 climate anomalies across Western Europe in the spring, summer and autumn of 1258 (Fig. 1). Notably,
 72 such abundant and detailed documentation in mediaeval archives is reserved for extreme
 73 meteorological events: the only comparable episode, reported in more than 30 sources (Text S1),
 74 relates to an extremely cold winter in Europe in 1233/34²¹.
 75

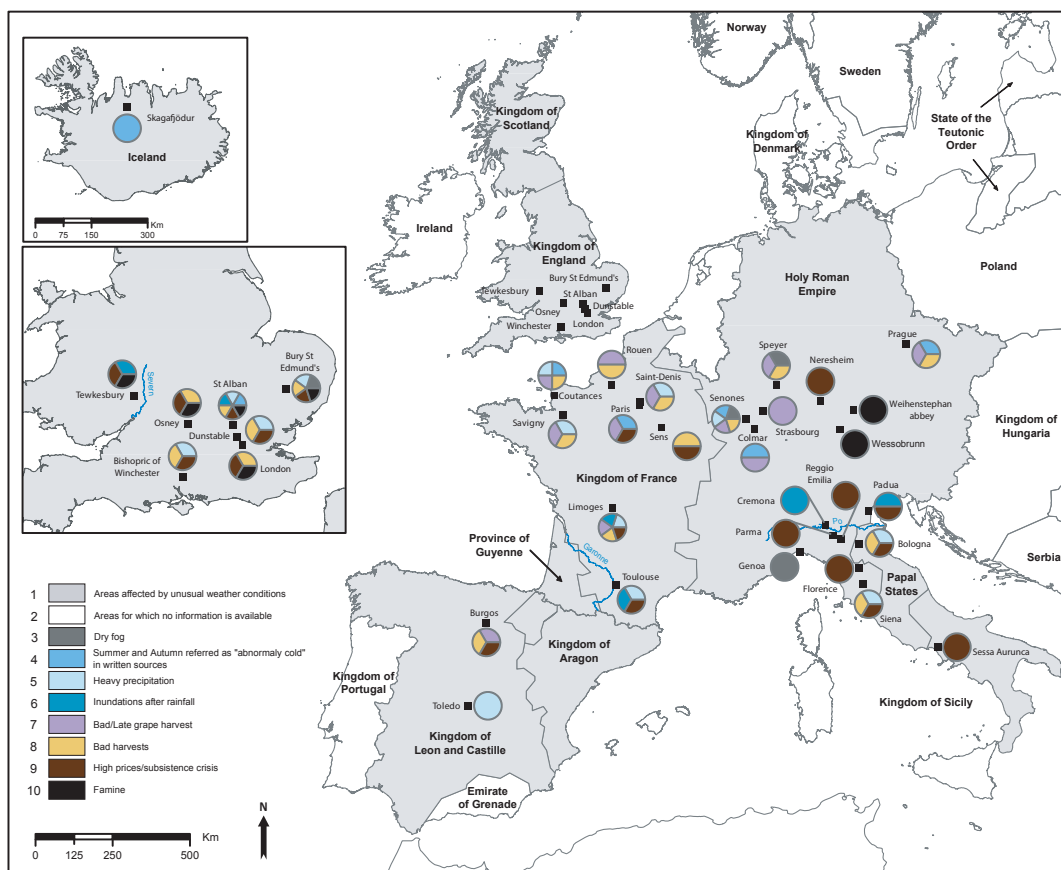


Figure 1. Spatial extent of weather and optical anomalies observed in Europe in 1258. All sources are listed in Table S1.

76 Without exception, all chronicles surveyed report cold, incessant rainfall and unusually high cloudiness
 77 in 1258, which prevented crops and fruits from reaching maturity. The *Norman Notes of Coutances*
 78 provides a good example: “*There was no summer during summer. The weather was very rainy and cold*
 79 *at harvest time, neither the crop harvest nor the grape harvest were good. Grapes could not reach*
 80 *maturity; they were green, altered and in poor health*”. This prefigures abundant descriptions of
 81 impacts on crops of the “Year Without a Summer” in 1816, a year after the Tambora eruption^{14,22,23}.
 82

83 Reports of poor quality grapes and late harvests (Fig. 1) span Western Europe from Burgos (Spain) to
 84 Prague (Czech Republic), but quantitative information on grape harvest dates (GHD) could only be
 85 retrieved for France. In Alsace-Lorraine, *Richer of Senones* reports that grapes were still green and as
 86 “hard as stone” on 8 October 1258 and that the harvest was postponed until the end of October (i.e.,
 87 circa day 305 of the year; doy), as winemakers were hoping for improved weather conditions in
 88 autumn (Methods and Text S2). In Paris, the *Annales Clerici Parisiensis* point to a GHD start on doy
 89 312 (Fig. 2a, Fig 3b), whereas in Burgundy, the start of GHD was estimated to doy 302 (Methods and
 90 Texts S2, S3). If compared with existing GHD series from Alsace-Lorraine (1700-2005), Ile-de-France
 91 (1478-1977) and Burgundy (1354-2006), we find that these are by far the latest dates ever observed,
 92 and that grape harvest started 7 (doy 298), 16 (doy 312), and 6 (doy 296) days later than in the 1816
 93 “year without a summer”. Using Extreme Value Theory, we find that the return period of the 1258
 94 GHD exceeds 1000 yr for the three regions (as compared to circa 100 yr for 1816) and that it reaches
 95 infinite values if known volcanically-influenced years are excluded from the analyses. This suggests
 96 that their occurrence is exceedingly unlikely to be related to interannual climate variability (Methods
 97 and Text S3). We caution, however, that the GHD approach does not account for possible changes in
 98 grape varieties or in agricultural and/or anthropogenic practices over time. As such, the return periods
 99 here are merely indicative of the unusual character of the grape growing season – which is controlled
 100 by maximum April-September temperatures²⁴ – over Western Europe in 1258 (Fig. 2b).

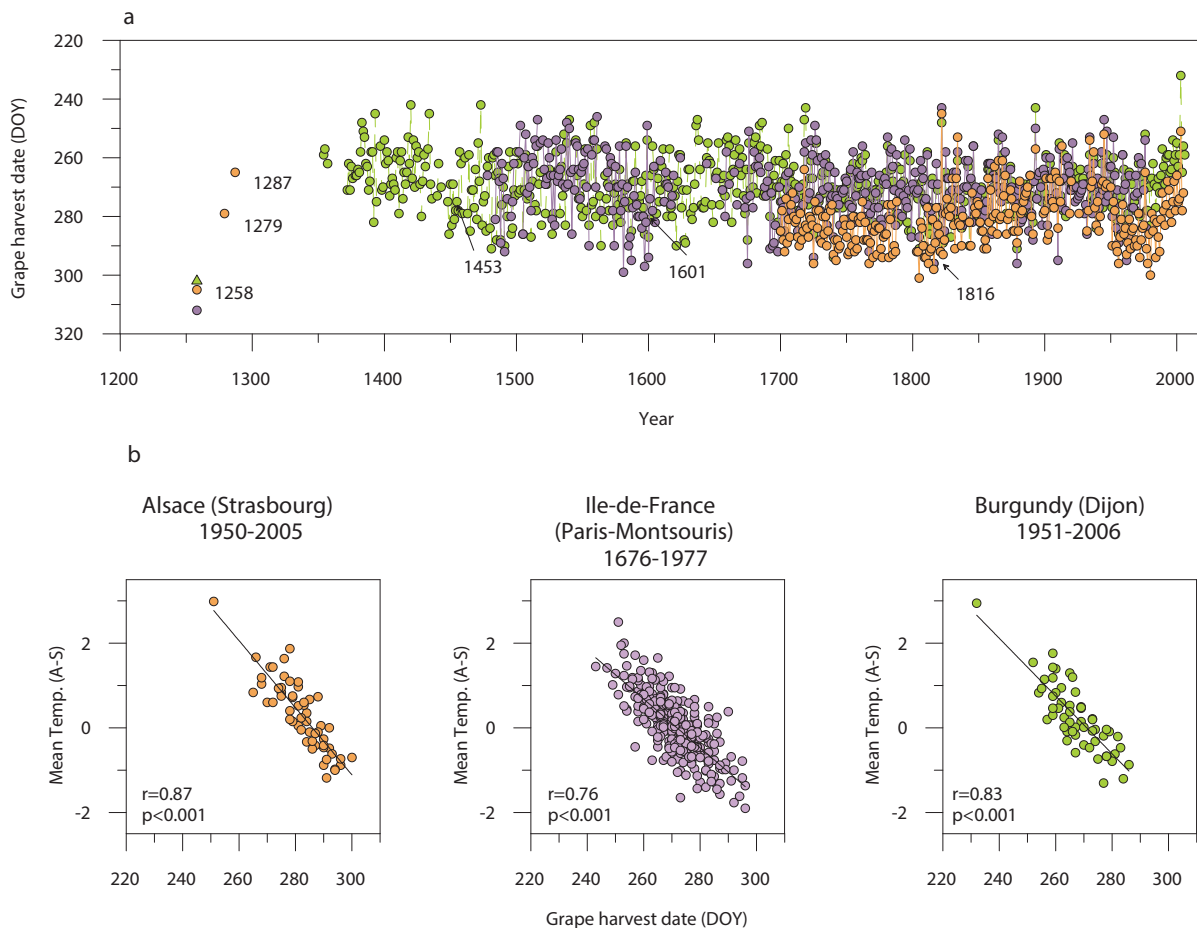


Figure 2. Grape harvest dates in France (1258-2006). a, Continuous records of days of year (doy) on which GHD occurred for Ile-de-France (purple), Alsace (orange) and Burgundy (green) between 1350 and 2006. Data are complemented by newly discovered sources for the years 1258, 1279, and 1294. The green star indicates the estimated 1258 GHD in Burgundy (Text S3). The most delayed grape harvest of the last 800 years occurred in 1258. See Table S1 for a list of all sources. b, GHD for Ile-de-France, Alsace, and Burgundy are significantly correlated with April-September mean air temperatures of the Paris-Montsouris, Strasbourg and Dijon meteorological stations.

102 The likely volcanic origin of the extreme cooling is reinforced by two accounts attesting the presence
 103 of a persistent dust veil (Text S4) over Europe in 1258. In Germany, the *Annals of Speyer* reveal that
 104 this year was commonly referred to as a *munkeliar* (Fig. 3a), meaning *dark year* or *year of fog* in
 105 contemporary German. The presence of a dense dust veil is corroborated by a detailed testament of a
 106 very dark (Danjon L=0; Methods, Text S4), total lunar eclipse²⁵ on 12 November 1258 in the *Annales*
 107 *Ianuenses* (Genoa, Italy). It complements the previously known dark lunar eclipse described in the
 108 Chronicle of *John de Taxster* (England) for 23 May 1258 (ref. 5). Beyond Europe, only a very limited
 109 number of contemporary narrative sources have hitherto been surveyed for evidence of climate
 110 anomalies. The *Mirror of the East* (Azuma Kagami, Kamakura, Japan) is an exception²⁶ and reports a
 111 wet and cold summer accompanied by heavy rain and strong winds, which reportedly destroyed
 112 paddies and gardens in several provinces.

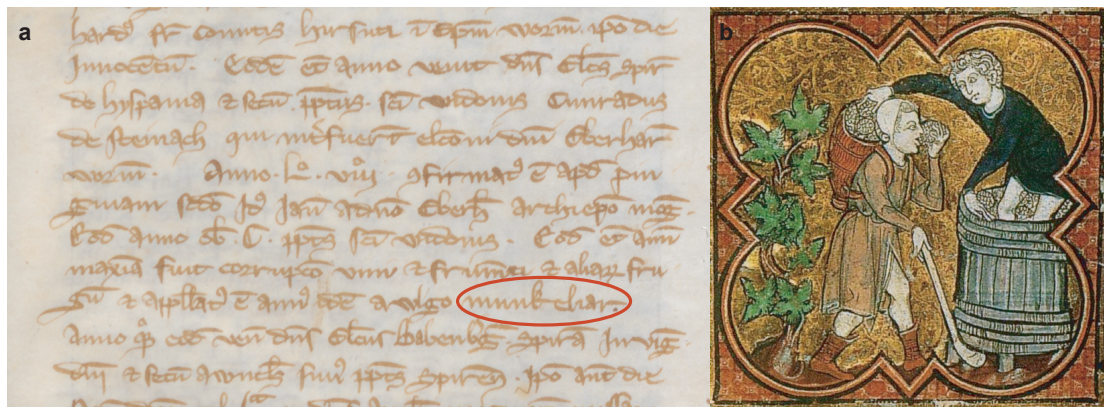
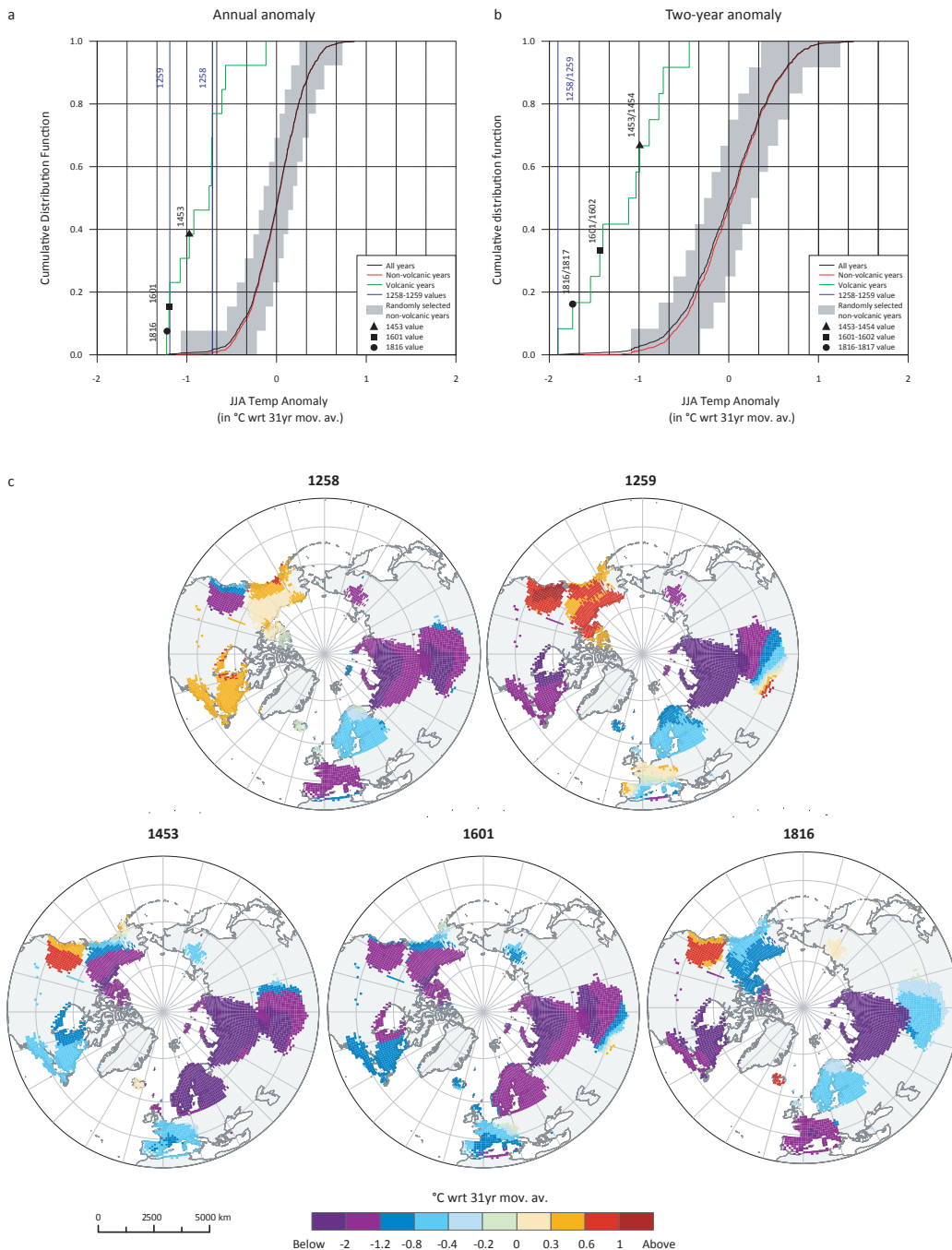


Figure 3. Original contemporary manuscript from the annals of Speyer describing the dust veil and climate anomalies observed in 1258 CE. a, The text in Latin says: “The same year, wine, wheat and other fruits were greatly altered and this year was also commonly referred to as *munkeliar*”. The use of the Middle High German expression *munkeliar*, rather than its Latin equivalent (*annus obscuritatis* or *annus caliginis*), suggests that the exceptional persistence and intensity of insolation dimming was not only omnipresent but unusual enough for commoners to give it a proper name (Source: Speyrer Kopialbuch. Generallandesarchiv Karlsruhe GLA 67 Nr. 448 fol. 39v). b, Contemporary illustration of wine harvesting as illustrated in the Martyrology of the Saint-Germain-des-Prés Abbey (Source: National Library of France, Paris, Ms lat. 12834, fol. 69v).

113 Magnitude of NH summer cooling inferred from proxy records

114
 115 Complementary information is provided by paleoclimate archives. We have used a tree-ring network
 116 covering the period 1000–2000 CE to quantify and map climatic anomalies induced by the Samalas
 117 eruption and, in particular, for those regions of the NH which remain unrepresented by mediaeval
 118 archives (Fig. S1, Table S2). All of the 25 chronologies span the 13th century and are significantly
 119 correlated with summer (JJA) temperatures (Fig. S2). A JJA NH temperature reconstruction (40–90°N
 120 over land) was generated using a nested approach containing 12 nests that account for the decrease in
 121 the number of regional chronologies back in time. Each nest passed all verification tests (R^2 and RE for
 122 the calibration period, as well as r^2 and CE for the verification period, see Methods and Table S3) for
 123 the period 1805–1972. The most replicated nest (1230–1972, $n=25$) accounts for 41% of the variance in
 124 the instrumental data with RE=0.37 and CE=0.34, demonstrating the robustness of the reconstruction
 125 for the 13th century. To quantify cooling with respect to contemporary climatology, the reconstruction
 126 was filtered with a 30-yr running mean (see Methods). We find that the cumulative distribution
 127 functions for all major volcanic eruptions and non-volcanic years differ in a statistically significant
 128 manner (Kolmogorov-Smirnov test, $p<0.001$) (Fig. 4a). Extreme average surface cooling occurred in
 129 1259, reaching -1.2°C , making it the third coldest summer since at least 1200 CE, whereas 1258
 130 (-0.7°C), 1601 (-1.2°C), 1453 (-1°C), and 1816 (-1.2°C) rank as the 16th, 2nd, 7th, and 1st coldest years
 131 in the series, respectively. If JJA temperature anomalies are summed for the two years after an eruption

132 (Fig. 4b), the Samalas eruption is seen to be associated with the strongest cooling anomaly of the last
 133 millennium.



134
 135 **Figure 4. Tree-ring reconstructions of NH extra-tropical land (40–90° N) summer temperature anomalies**
 136 **since 1000 CE. a,** Summer (JJA) temperature anomalies following the 1257 Samalas eruption in 1258 (red) and
 137 1259 (blue) as compared to cumulative distribution functions (cdf) for all major volcanic eruptions (i.e., 1109,
 138 1453, 1601, 1641, 1695, 1783, 1809, 1816, 1835, 1884, and 1912; black) and for all non-volcanic years (red) since
 139 1000 CE. **b,** same as in a, but for groups of two consecutive years following major eruptions. **c,** Spatial extent of
 140 the JJA temperature anomalies induced by the Samalas (cooling shown for 1258 and 1259), unknown (1453),
 141 Huaynaputina (1601), and Tambora (1816) eruptions. For details see Methods.

142 **Spatial heterogeneity of NH summer cooling**

143

144 The 25 chronologies were grouped into 11 clusters to estimate regional variability of summer cooling
 145 induced by the Samalas eruption, and complemented with three annually-resolved, summer season

146 stable oxygen isotope $\delta^{18}\text{O}$ series from Greenland ice cores (GRIP, Crete, DYE3). The spatial extent of
147 each cluster was defined via spatial fields of correlation between each proxy record and mean JJA
148 temperatures of the Berkeley Earth Surface Temperature (BEST) dataset²⁷ (Fig. S2). Based on this
149 approach, Greenland ice cores provide information on temperature in Eastern Greenland and Iceland.
150 The JJA gridded temperature reconstruction (3486 $1^\circ \times 1^\circ$ grid points with a CE>0.1, Fig. S3) is given
151 for 1258, 1259, 1453, 1601, and 1816 (Fig. 4c).

152

153 For all these years, volcanic forcing induced pronounced cooling over Siberia and, to a lesser extent, in
154 Western Europe. Less consistent patterns are observed in Alaska and on the Western Pacific Coast. In
155 1258, Western Europe, the Canadian Rockies, Central Asia and Siberia were the most severely affected
156 with a reconstructed cooling between -1.4 and -2°C (wrt 30-yr climatology). The extremely cold
157 conditions prevailing in Siberia and Central Asia are further corroborated by the presence of frost rings,
158 which have previously been recognized as a response to severe cooling associated with volcanic
159 forcing of climate²⁸ (Table S4).

160

161 In contrast, the Greenland ice core cluster (-0.1°C , rank 408) and tree-ring records from Quebec
162 ($+0.5^\circ\text{C}$, rank 676), Alaska ($+0.3^\circ\text{C}$, rank 617) and, to a lesser extent, Scandinavia (-0.5°C , rank 264)
163 do not reveal pronounced cooling, suggesting that, in these regions, internal modes of climate
164 variability outweighed the direct radiative effects of volcanic aerosol. The warm anomalies over Alaska
165 in 1258-9 (Fig. 4c) could arise from a positive phase of the Pacific-North-Atlantic pattern, linked to
166 ENSO (Fig. S4). Climate simulations and proxy records indeed show increased probability for an El
167 Niño event to occur in the first or second year after a large volcanic eruption²⁹⁻³¹. This assumption is
168 further confirmed by El Niño conditions inferred for 1258/59 from tree-ring and sediment proxies²⁹.

169

170 We also use tree-ring records and historical archives to investigate the persistence of volcanically-
171 induced cooling. Interestingly, Fig. 4c shows that several regions experienced maximum cooling only
172 in 1259, i.e., two years after the eruption. In Quebec, for instance, the strong negative anomaly in 1259
173 likely results from extremely cold conditions at the end of the previous growing season, as revealed by
174 the presence of light rings in the latewood of 1258 (Table S4). This lag effect, known as autocorrelated
175 biological memory³², is often observed in tree-ring width (TRW) series and reflects the influence of
176 climatic and physiological conditions prevailing in the year prior to tree-ring formation (e.g., via needle
177 generation, or the creation of carbohydrate reserves). In Siberia, however, biological memory cannot
178 fully explain the temperature drop in 1259, because frost rings in the Yamal, Polar Ural, Altai, and
179 Mongolian tree-ring chronologies (Table S4) as well as historical records documenting abundant
180 snowfall in the Altai in July clearly confirm the extreme cooling experienced in these regions in
181 summer 1259 (ref. 33).

182

183 Based on the available data, the only regions to experience mild conditions in the summer of 1259 were
184 the Pacific coast of North America (as identified in tree-ring records) and Western Europe, for which
185 five historical sources were found (Text S6). In the *Annales Wormatienses* (Germany), it is stated that
186 *on the day of the Apostles Peter and Paul [29 June], the summer was hot and dry. From March to*
187 *August, little or even no rain fell, however wine and all other fruits of the earth were abundant.* Tree-
188 ring proxies and chronicles indicate a general reduction in all climatic anomalies by 1260 and 1261
189 (Text S7), and thus provide strong evidence that the impacts of the eruption ceased after 3-4 yr (Fig.
190 S5). This points to a more ephemeral effect on climate than suggested by computational models that
191 exclude aerosol microphysics, which predicted a persistence of temperature anomalies over
192 extratropical land of the order of -1°C until 1264 (ref. 34).

193

194 The estimated hemispheric cooling following the Salamas eruption is comparable to that observed for
195 1453, 1601, and 1816, although Samalas released substantially more sulphur to the atmosphere than the
196 other volcanic events. This underlines the hypothesis that volcanic cooling does not increase linearly
197 with the total sulphur yield of an eruption^{20,35}. In addition, we confirm that the magnitude and

198 persistence of cooling resulting from the 1257 event were much smaller and shorter, respectively, than
199 predicted in PMIP3 simulations. The disparity is sufficiently great that the Samalas eruption can no
200 longer be held responsible for a dramatic and persistent cooling of continental regions of the NH⁸.
201 Evidently, the largest eruption of the Common Era only induced “years without summer” in certain
202 regions, but not across the entire NH. This finding is consistent with observations in 1816, and points
203 to the modulation of radiative forcing effects of volcanic aerosols by internal climate variability (e.g.,
204 ENSO, NAO)²³. Our reconstructed patterns of spatially heterogeneous temperature anomalies provide
205 crucial constraints for the evaluation of climate model performance for the 1257 Samalas event and
206 other high sulphur yield eruptions in the tropics.

207

208

209 **Complex societal response to the Samalas eruption**

210

211 It has been posited that a cluster of volcanic eruptions in 536, 540 and 547 may have played a crucial
212 role in the rise and fall of several polities, pandemics and human migration¹¹. Several sources point to
213 severe food shortages and subsistence crises in parts of Europe (Kingdom of France, Kingdom of
214 England, Holy Roman Empire, Iberian Peninsula) in 1258 and 1259, although they were less
215 widespread and shorter than the famines of 1195-1197, 1233-1235 or 1315-1319 (ref. 36,37), which
216 cannot be associated with volcanic events. The most severe socio-economic consequences reported at
217 the time of the Samalas eruption are from England, where the 1258 famine caused by two consecutive
218 years of bad harvests (1256-57), high prices and speculation may have killed about 15,000 people in
219 London alone³⁸. Likewise, the Shōga famine (Japan, 1257–1260) was possibly amplified by adverse
220 climatic conditions in 1258 and 1259 (ref. 26). In both cases, we conclude that volcanic forcing of the
221 climate following the Samalas eruption played a role in aggravating these crises, but should not be
222 considered as the trigger for the famines or related social unrest. This emphasizes the complexity of
223 identifying causal connections between individual cases of volcanically induced climate anomalies and
224 major societal upheavals³⁹.

225

226 **Methods**

227

228 **Analysis of historical sources.** We exhaustively reexamined 180 annals and chronicles (original and edited
229 manuscripts, Table S1, Figs. 1-2), written in the 13th century to document the climatic impacts of the Samalas
230 eruption. Sources were mostly in Latin and to a lesser extent in the vernacular (Old French, High Middle German,
231 and Old Castilian). From this corpus, 59 narrative sources were from Western Europe and report weather and
232 phenological (crop and grape harvest dates) observations for the years 1257, 1258, 1259, 1260 and 1261 (Table
233 S1). Particular attention was also paid to historical reports of optical phenomena attesting to the presence of
234 volcanic aerosols in the stratosphere²⁵ (e.g., dimming of the Sun, dark total lunar eclipse, Text S4). The reliability
235 of eclipse observations was further assessed through the catalogue of five millennia of lunar eclipses (1999 BCE –
236 3000 CE)⁴⁰. The darkness of the moon was rated according to the Danjon scale⁴¹ ranging from L=0 (very dark) to
237 L=4 (very bright copper-red or orange). The focus was clearly on first-hand information derived from
238 contemporary sources, and dates in chronicles were screened systematically for errors by cross-checking
239 information with other manuscripts.

240

241 **Analysis of grape harvest dates.** Mediaeval grape harvest dates (GHD) obtained from Saint-Denis and Senones
242 Abbeys were added to GHD series available for the French regions of Alsace and Ile de France²⁴. Mediaeval dates
243 were first converted to Gregorian calendar by adding 7 days to Julian calendar and then expressed as day of the
244 year (doy). Correlation analyses were performed against April-September temperatures from Paris-Montsouris
245 (1676-1977) (ref. 42), Dijon (1951-2006) and Strasbourg (1950-2005) (<https://climexp.knmi.nl/>) to assess the
246 suitability of GHD as a temperature proxy (Fig. 2). Missing values were calculated on the basis of inter-series
247 similarity, allowing estimation of the 1258 GHD in Burgundy. For all three series, extreme GHD were selected as
248 the 10% latest dates. The three estimated datasets as well as a composite record were fitted using the discrete
249 version of the Generalized Pareto Distribution (GPD), leading to four estimates of the 1258 GHD return period.
250 Also, the analysis was duplicated, excluding the sample of years corresponding to known large volcanic eruptions
251 from the GPD fitting, providing estimates of the 1258 GHD return period under unperturbed climate conditions
252 (Text S3).

253

254 **Tree-ring chronology selection and assessment.** We compiled an extensive database of tree-ring width (TRW
255 and maximum latewood density (MXD) chronologies from the International Tree-Ring Database (ITRDB) and
256 published papers from NH tree-line sites located between latitudes 39 and 73°N (Table S5). For each individual

257 chronology, we carefully tested its sensitivity to June-August (JJA) temperatures (Fig. S2) and excluded series
258 with an ambiguous climate response. The remaining 25 chronologies (13 TRW and 12 MXD) all include the 13th
259 century; they were grouped into 11 regional clusters based on correlation matrices ($r > 0.3$, p -value < 0.05). All
260 clusters document the Samalas eruption with an expressed population signal or EPS never < 0.85 .

261
262 **Tree-ring based NH temperature reconstruction.** Each cluster was standardized using standard (i.e., negative
263 exponential), RCS^{43,44} and Signal-Free RCS⁴⁵ standardizations that preserve low-frequency (that is, multi-decadal)
264 temperature changes. We then transferred this record into JJA temperature anomalies (wrt 1961–1990) through a
265 bootstrap linear model using principal component analysis calibrated against JJA land surface temperature
266 anomalies (1805–1972) from the BEST dataset²⁷. The calibration and validation process was repeated 1,000 times
267 using a bootstrap method to assess the robustness of the transfer function. To test the quality of the fit of each
268 individual run, we used coefficient of determination statistics (R^2 for the calibration and r^2 for the verification
269 periods), whereas the RE (reduction of error) and CE (coefficient of efficiency) statistics served to test the
270 predictive capacity of the transfer function. Calibration and validation statistics are illustrated for each nest with
271 their 2.5 and 97.5 percentiles (Table S3) and the reconstruction is given with its 95%-confidence intervals (Text
272 S5). To account for the decreased number of chronologies back in time, we used a nested approach (12 nests) to
273 obtain the longest possible reconstruction. The final reconstruction was developed by splicing all the nested time
274 series after adjustment of mean and variance of each nested reconstruction segment to the best replicated nest
275 (1230–1972). This approach is known to stabilize the variance of the final reconstruction but to increase the error
276 variance. Calibration and validation statistics ($R^2 = 0.39$ – 0.45 , $r^2 = 0.35$ – 0.38 ; reduction of error $RE = 0.36$ – 0.39 ,
277 coefficient of efficiency $CE = 0.34$ – 0.37 ; see Table S3) were used to evaluate the reliability of the reconstruction. In
278 Fig. 4b, reconstructed temperature anomalies are presented as deviations from the climate mean climatology
279 smoothed with a 15-yr time window on either side of the volcanic eruptions dated to 1257, 1452, 1600, and 1815.
280 For example, in the case of Samalas, a background was calculated by averaging the window 1243–1257 and 1259–
281 1273. The anomaly is then created by subtracting this background from the 1258 reconstructed temperature. As for
282 GHDs, the 10% lowest values were fitted using the continuous GPD to evaluate the return period of the cooling
283 induced by the Samalas and by other big eruptions. Analysis was done for the 1258 and 1259 annual values, as
284 well as for anomalies cumulated over two years (Fig. 4).

285
286 **Regional reconstructions.** To account for the spatial variability of volcanic cooling, the 25 tree-ring chronologies
287 were grouped into 11 clusters. In addition, to extend the analysis to other unrepresented regions we included a
288 cluster of three stable isotope series from Greenland ice cores (GRIP, Crete, DYE3), all statistically significantly
289 related to summer temperature conditions over Eastern Greenland and Iceland⁴⁶. The spatial extent of each cluster
290 was defined via the spatial field of correlations between each proxy record and mean JJA temperatures of the
291 BEST dataset (Fig. S2). We then applied linear regression analysis (for clusters with only one chronology) or a
292 bootstrap linear model using principal component analysis (for clusters with multiple chronologies) in order to
293 calibrate cluster series to JJA gridded temperature anomalies (wrt 1961–1990) from the BEST dataset. Full period
294 calibration was performed separately for each of the 12 clusters over the period 1901–1990 while the robustness of
295 this association was tested through cross-validation procedures for the period 1901–1945 and 1946–1990 (Fig. S3).
296 Only grid points with a $CE > 0.1$ were used for the spatial representation of temperature anomalies.

297
298 **Data availability.** The data used to perform our analysis as well as our results can be accessed at:
299 <https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-reconstruction>

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394 S.G., C.C., M.S. and F.L. designed the research. S.G. investigated historical archives and translated the narrative
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396 and C.C. produced the NH reconstructions with input from N.E. and J.G. for statistical analyses. O.C.S., N.D.,
397 J.L.E., Y.Z., V.S.M., P.O., V.M.D. provided data for the elaboration of the proxy network. S.G., C.C., M.S., C.O.

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401

402 **Additional information**

403

404 Supplementary information is available in the online version of the paper Correspondence and requests for
405 materials should be addressed to S.G.

406

407 **Competing financial interests**

408

409 The authors declare no competing financial interests.