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Climate response to the Samalas volcanic eruption in 1257 revealed by proxy records

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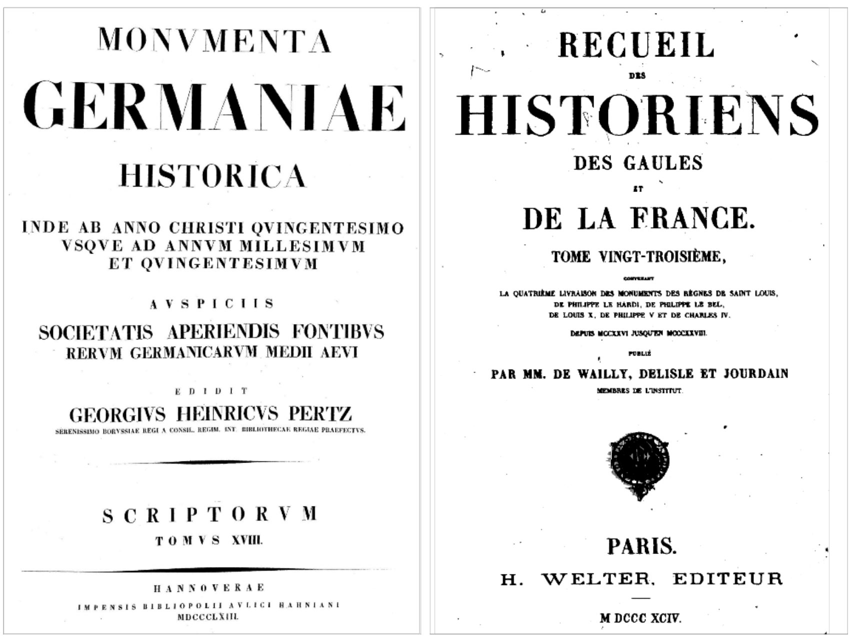
Documentary sources describing the weather anomalies and unusual optical phenomena observed in Europe in the aftermath of the 1257 Samalas eruption

Meteorological and astronomical information used to describe the climatic aftermath of the 1257 Samalas eruption in Europe were mainly extracted from contemporary narrative sources. Those contemporary sources have been found in a compilation of mediaeval texts edited in the series of the *Monumenta Germaniae Historica* (Figure 1a) during the 19th century. We have also investigated the *Rerum Britannicarum Medii Ævi scriptores* and the *Annales Monastici* often simply known as "*The Rolls Series*". The *Recueil des historiens des Gaules et de la France* (Figure 1b), the *Rerum Italicarum scriptores* as well as the *España sagrada* have also been surveyed.Two main types of narrative sources can be distinguished: Annals and chronicles. Annals are commonly referred by modern historians as a brief and simple listing, year by year, of significant events or prodigies that have to be remembered, such as years of Kings' reign, campaigns but also sometimes natural hazards, eclipses and comets. At the opposite, descriptions provided by chronicles tend to be less concise, more detailed and also more "story-like" (*Pfister et al., 1998*). Most of the annals and chronicles used in this paper were written in Latin and to a lesser extent in the Vernacular (i.e. Old-French, High Middle German or Old Castilian). All primary sources studied were written in England, France, Germany, Italy, Spain or the Czech Republic.

a) b)


MONVMENTA
GERMANIAE
HISTORICA
INDE AB ANNO CHRISTI QVINGENTESIMO
VSQVE AD ANNVM MILLESIMVM
ET QVINGENTESIMVM
AVSPICIIS
SOCIETATIS APERIENDIS FONTIBVS
RERVM GERMANICARVM MEDII AEVI
EDIDIT
GEORGIVS HEINRICVS PERTZ
SERENISSIMO BORVSSIAE REGI A CONSIL. REGIM. INT. BIBLIOTHECAE REGIAE PRAEFECTVS.
SCRIPTORVM
TOMVS XVIII.
HANNOVERAE
IMPENSIS BIBLIOPOLII AVLICI HAHNIANI
MDCCCLXIII.

RECUEIL
DES
HISTORIENS
DES GAULES
ET
DE LA FRANCE.
TOME VINGT-TROISIÈME,
CONTENANT
LA QUATRIÈME LIVRAISON DES MONUMENTS DES RÈGNES DE SAINT LOUIS,
DE PHILIPPE LE HARDI, DE PHILIPPE LE BEL,
DE LOUIS X, DE PHILIPPE V ET DE CHARLES IV.
DEPUIS MCCXXVI JUSQU'EN MCCCXXVIII.
PUBLIÉ
PAR MM. DE WAILLY, DELISLE ET JOURDAIN
MEMBRES DE L'INSTITUT.
PARIS.
H. WELTER, EDITEUR
M DCCC XCIV.

Figure 1. a - Volume 18 of the *Monumenta Germaniae Historica*, b - Volume 23 of the *Recueil des historiens des Gaules et de la France*. In these two compilations were edited several primary sources used in this study.

To the present day, 59 narrative sources providing information the climatic aftermath of the AD 1257 Samalas eruption in Western Europe (i.e, the years 1257, 1258, 1259, 1260 and 1261) could be found. All the sources are described in Table S1 (see the additional excel file).

Out of these 59 sources, 40 sources were written contemporaneously by an author who very likely witnessed himself the events he depicts. The content of the source is said to be original. These sources are generally the most reliable.

6 sources were considered as duplicates. It means that the author that wrote the source did not witness himself the event he described but copied the information from another sources. The content is not original. The duplicates were listed in the table S1 but were not used for the analyses.

We also found 13 sources that do contain valuable information about the aftermath of the Samalas eruption, but that were compiled later using earlier sources that are now lost to us (see Table S1 for further details).

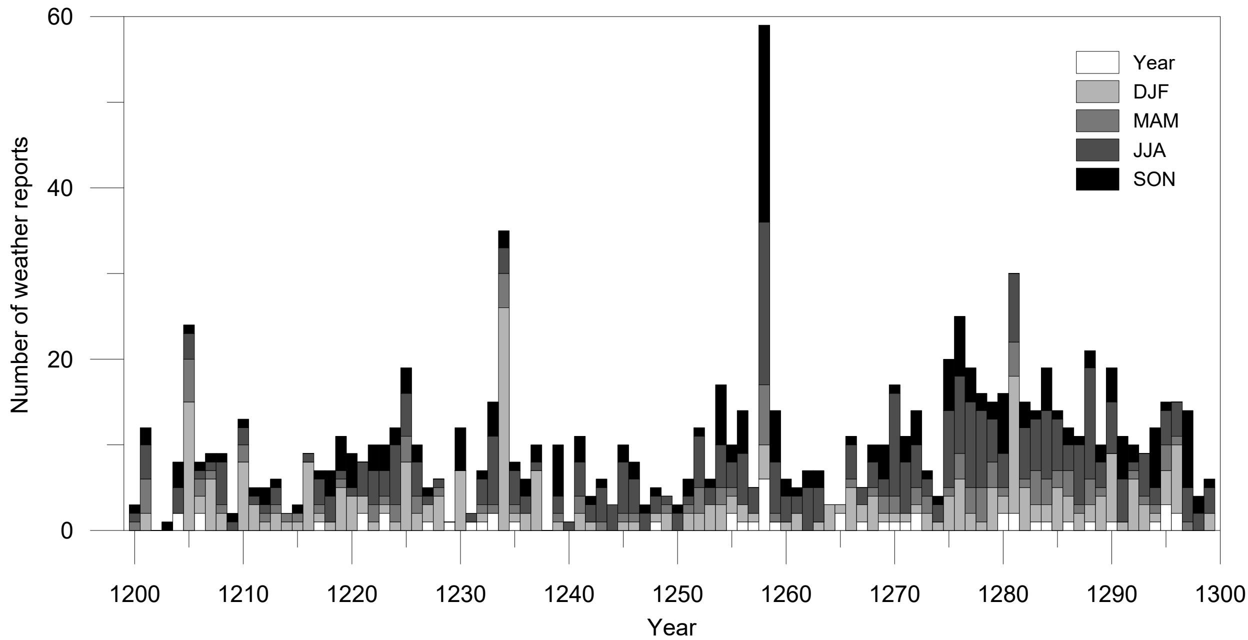


Figure 2. Number of weather reports per year and season over the 13th century. Clear peaks are observed following the severe winter of 1204-1205, 1233-34, 1280-1281 and the cold and wet summer and autumn of 1258.

During the investigation of narrative sources, we did not only focus our survey on the years 1257, 1258, 1260 and 1261, we also tried to extract, when available, weather reports documented for other years of the 13th century. Figure 2 illustrates the number of weather reports in narrative sources found for each year of the 13th century, separated by season (winter - DJF, spring - MAM, summer - JJA, and autumn SON).

180 annals and chronicles have been investigated but it should also be stressed that only a fraction of the available historical archival records has been studied so far and that the time series presented in the Figure 2 does not represent for the 13th century all the existing weather reports. The present time series is mostly based on weather entries

found in the *Monumenta Germaniae Historica, the Rerum Britannicarum Medii Aevi Scriptores*, *Recueil des historiens des Gaules et de la France*, *the Rerum Italicarum Scriptores* and to a lesser extent the *España sagrada*. For the years for which we did not have any weather report, we used the weather records compiled by Alexandre (1987).

The year 1258, with 58 reports, stands as one of the years for which we could retrieve the largest number of weather observations in Western Europe, along with the severe winters of 1204/1205, 1233/1234 and 1280/1281 This suggests that weather conditions in 1258 were indeed sufficiently anomalous to be deemed worthy of a written statement (Figure 2).

Out of these 58 accounts, 4, 6, 19, and 23 accounts, respectively, provide information about the weather conditions observed during the winter (DJF), summer (JJA), and autumn (SON) of 1258. Another 7 accounts provide information about the general character of the year but without giving details about a specific season (Figure 2).

A clear trend toward a greater number of weather records can be observed after the 1260s. This trend may be associated with the increasing number of sources available at the end of the 13th century. By contrast, the spike in reports on anomalous weather in 1258 cannot be considered the result of more sources being available during that particular year.

Text S2. Recovering the grape harvest dates (GHD) recorded in Europe following the 1257 Samalas eruption.

1- Introduction

The validity of grape harvest date records (GHD) as a robust temperature proxy has long been debated (Guerreau 1995, Rutishauser et al., 2007; for a full discussion see also García de Cortázar-Atauri et al., 2010). Several researchers have indeed shown that spring-summer temperatures are not the only factor influencing/deciding when grapes are to be harvested. The changes in agricultural practices, the use of different grapes varieties in a same region over time, as well as the political background (e.g. military conflicts for instance[1], Garnier et al., 2011) can also influence harvest dates and bias the climate signal contained within the GHD series.

However despite the aforementioned limitations the generally high negative correlation between GHD series and April-August/September temperature instrumental data (Chuine et al., 2004; Meier et al., 2007) has led to the conclusion that GHD can provide valuable and additional information about spring and summer temperatures for non-alpine regions of Europe where temperature-sensitive trees are rarely available. Thus over the past few years a growing number of studies have used grape harvest dates (GHD) as a complement to tree rings to reconstruct past temperature variability in western and central Europe (Chuine et al., 2004; Meier et Pfister, 2007; Maurer et al., 2009; Garnier et al., 2011).

Most of the longest GHD series have been developed in France (Burgundy series, Chuine et al., 2004, Ladurie et al., 2006; Ile-de-France series, Daux et al., 2012) and Switzerland (Meier et al., 2007) and reach back with some gaps to the 14th and 15th centuries respectively. No GHD record extending back to the 13th century and to the year 1258 has so far been made available.

In the following section (section 2) we reproduce all the Latin texts that were used to extend the grape harvest records developed by Daux et al. 2012 back to the 13th century, as well as their English translations. We feel that giving the reader the opportunity to discover the full description of the original texts used in this study is important as it is probably the best way to understand how contemporaries coped/dealt with the climatic perturbations induced by the Samalas eruption. In the section 3 we check upon the validity of the documentary evidence used in the study.

2- Written sources used to recover the GHD series for the year 1258

In 1258, the grape harvests were so late, exceptional and noteworthy that several chroniclers decided noteworthy to provide some information on the date the grapes were collected. Thus, the *Annales Clerici Parisiensis* (Paris, Ile-de-France region) state that in 1258 the grape harvests started around the 1st of November (Figure 3). This date is expressed according to the Julian calendar and has to be converted to the Gregorian calendar by adding 7 days, which corresponds to the 8 of November (doy: 312). Here we provide the original text as well as the ensuing English translation:

[1] *Grapes were sometimes picked before full maturity in case of loss to plundering armies. Thus, early vintages were not always the result of warm summers.*

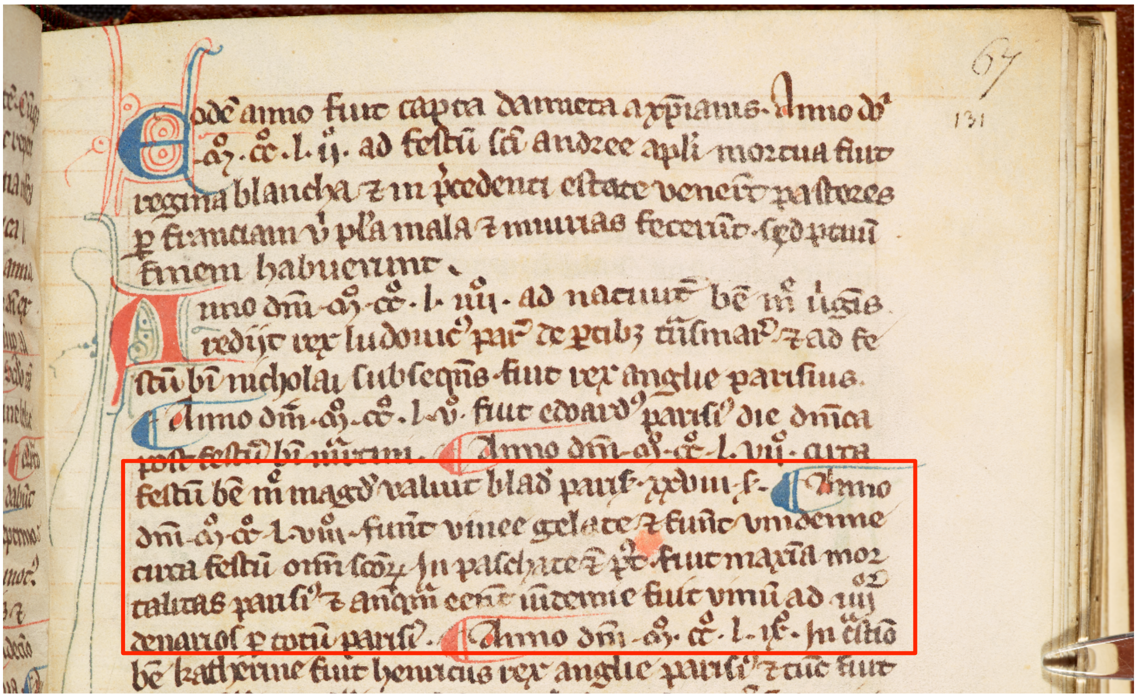


Figure 3. Original manuscript of the Annales Clerici Parisiensis (13th century). London, British Library, Cotton MS Vespasian D IV, folio 67v.

1258:

Anno Domini M CC LVIII, fuerunt vinee gelate, et fuerunt vindemie circa festum omnium sanctorum. In Paschate etiam post fuit maxima mortalitas Parisius, et antequam essent vindemie fuit vinum ad IIII^or denarios per totum Parisius.

Notes sur quelques Manuscrits du Musée Britannique – Annales Clerici Parisiensis, DELISLE L. (ed.), 1877. Mémoires de la Société de l'Histoire de Paris et de l'Ile-de-France, Vol. 4, H Chambon, Libraire de la Société de l'Histoire de Paris, Paris, pp. 187-190.

Translation:

Year of the Lord 1258, vineyards were frozen and grape harvest occurred around All Saints' Day (1st of November). At Easter time[2] there was a large mortality in Paris, and before the harvest the wine was sold 4 deniers[3] in all Paris.

[2] *The Annales Clerici Parisiensis here probably refers to the year 1259. Through the Middle Ages various New Year dates were used. In Paris, since the reign of Philip II Augustus (1180-1223), the year usually started on Easter day (Giry, 1925). In 1259, Easter occurred on the 13th April 1259. Considering that the epidemic stroke Paris in 1259 would be consistent with the Annales of Coutances which also place the beginning of the epidemic in Paris around April 1259 (see Text S6, page 34).*

[3] *From the reign of Philip II Augustus (1180-1223), the most common system of money in France was based on the livre tournois, or pound of Tours. A pound was divided into 20 sols or sous (shillings, solidus), and the sol in turn into 12 deniers (pennies, denarii). But other systems of money coexisted such as the livre parisis (the pound of Paris). The pound parisis pound exceeded the pound tournois by one fourth, so that the pound parisis was 25 sols (375 deniers) and the pound tournois 20 sols (240 deniers).*

In Senones (northeastern France), the Chronicle of Richer describes with many details how the lack of sunlight, low temperature and frost-damaged greatly delayed the ripening of wine grapes, leading winemakers to begin harvests during the last days of October, 3 weeks later than usual (doy: 305). In 2000 Richard Stothers published in *Climatic Change* a small excerpt of the Chronicle of the monastery of Senones. Here we complete his work by publishing the second and last part of the text and its ensuing translation:

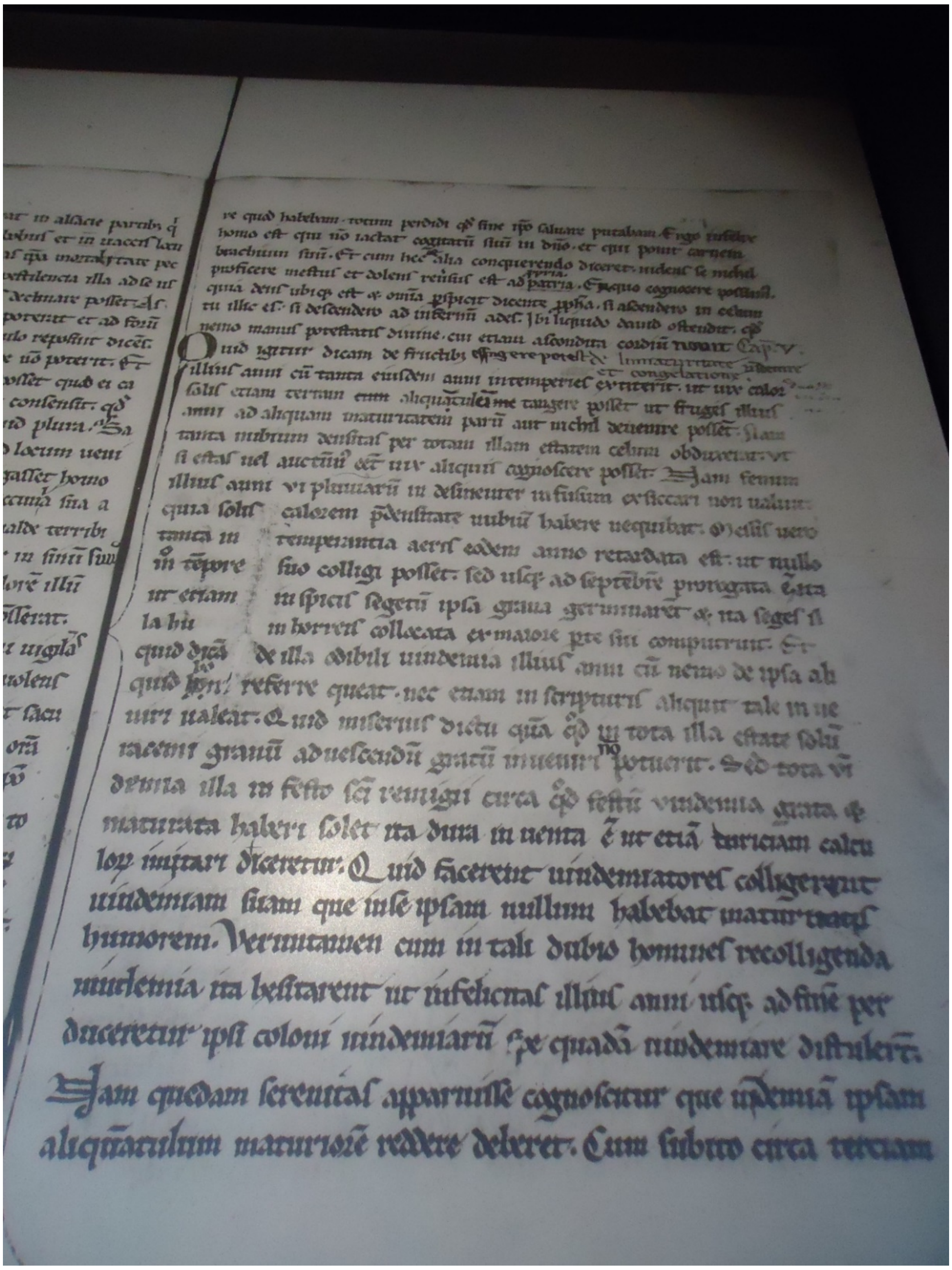


Figure 4. Microform reproduction of the Chronicle of Richer of Senones (MS. Latin 10016, French National Library, Paris).

De inmaturitate vindemie et congelatione.

Quid igitur dicam de fructibus illius anni, cum tanta eiusdem anni intemperies extiterit, ut vix calor solis etiam terram aliquantulum tangere posset, ut fruges illius anni ad aliquam maturitatem parum aut nichil devenire possent ? Nam tanta nubium densitas per totam ilam estatem celum obduxerat ut, si estas vel auctumnus esset, vix aliquis cognoscere posset.

Nam fenum illius anni vi pluviarum indesinenter infusum exsiccari non valuit, quia solis calorem pre densitate nubium habere nequibat. Messis vero tanta intemperantia aeris eodem anno retardata est, ut nullo modo tempore suo colligi posset, sed usque ad Septembrem prorogata est, ita ut etiam in spicis segetum ipsa grana germinarent, quia ita seges illa humida in horreis collocata ex maiore parte sui computruit.

Et quid dicam de ilia odibili vindemia illius anni, cum nemo de ipsa aliquid boni referre queat, nec etiam in scripturis aliquit tale inveniri valeat? Quid miserius dictu, quam quod in tota illa estate solum racemi granum ad vescendum gratum inveniri non potuerit? Sed tota vindemia ilia in festo sancti Remigii, circa quod festum vindemia grata et maturata haberi solet, ita dura inventa est, ut etiam duriciam calculorum imitari diceretur. Quid facerent vindemiatores? colligerent vindemiam suam, que in se ipsa nullum habebat maturitatis humorem?

Veruntamen cum in tali dubio homines de colligendas vindemia ita hesitarent, ut infelicitas illius anni usque ad finem perduceretur, ipsi coloni vindemiarum spe quadam vindemiare distulerunt. Nam quedam serenitas apparuisse cognoscitur, que vindemiam ipsam aliquantulum maturiorem reddere deberet. Cum subito circa terciam ebdomadam Octobris borea flante tantum gelu inhorruit, ut tota vindemia in una glacie congelaretur. Nec tantum in regione ista sed etiam in longe positis et remotis partibus mundi hoc infortunium fertur contigisse. Sed quid de hac miserabili vindemia evenerit, tacere non possumus. Nam cum viderent cultores vinearum vineas ipsas cum botris suis esse congelatas et cottidie vi frigoris ad maiorem duriciam perduci, spe maturitatis fraudati, ipsam vindemiam cogitaverunt colligere. Et ita collectam in saccis ad domicilia sua deportabant, et quomodo poterant in stupis vel in aliquibus locis calidis ipsos racemos degelabant et ita in torculari quantum poterant liquoris exprimebant et in vasis collocabant.

Sed unum interfuit, quod vindemia illa eo anno bene defecata est, sed vinum ilium potatum quandam amaritudinem et duriciam preferebat. Sed mirum dictu, in vasis ita maturescere cepit, ut, cum ad estatem pervenit, abilius potari poterat. Sed adhuc infelicitas illius anni non desinit esse; nam in hortis ut breviter loquar, aliqua olera seminata non creverunt, pira, poma ad grossitudinem solitam non pervenerunt neque saporem, quem aliis annis reddere solebant, non habebant. Ita annus ille per totum sui spacium ex omni parte miserabilem habuit decursum. Sed tamen pestilential pecorum ipso anno finiente non finivit, sed per totutn sequentem annum regiones plurimas bobus et vaccis penitus vacuavit. [...] Sed sequens annus tam temperatus et fertilis extitit, ut adeo bonis habundaret, ut iam nemo preteriti anni inordinationis non reminisceretur.

Richeri Gesta Senoniensis Ecclesiae, WAITZ G. (ed.), 1880. Monumenta Germaniae Historica, Scriptores 25, Hanover, pp. 249-345.

Translation:

On the immaturity and freezing of grape harvest

What, then, shall I say about the fruits of the earth that year, when the weather was so remarkably unseasonable that the warmth of the Sun was hardly able, even a little, to reach the earth, and the fruits of that year could barely attain maturity, if at all? For so great a thickness of clouds covered the sky throughout that whole summer that hardly anyone could tell whether it was summer or autumn.

The hay, drenched incessantly by strong rains that year, was unable to dry out and also the crops were so spoiled by rain and humidity that they could only be harvested in September. The grains germinated within the wheat heads still standing in the fields and once they were harvested and stored in the granaries, they rotted completely.

What can I say about the odious grape harvest of that year, since it appears that no one could gain any benefit nor emolument from it and that such an event was never heard of before? Even more terrible/miserable is that during the whole summer not a single ripe grape could be found, even around the feast day of Saint Remy (1st of October) at which time the grapes usually reach maturity. The grapes were as hard as stone. In such conditions, what could the wine-growers have done? Should they have harvested the grapes despite their unripeness?

After hesitating to gather their grapes, they collectively decided to delay the grape harvest due to the unseasonable weather in hopes that the grapes would ripen, for they noticed an improvement in the weather conditions. However their hopes were deceived as unfortunately, one day of the third week of October, the North wind in full strength, brought such a frost that all the grapes froze. This happened not only in this location but also in more distant regions. I cannot silence the misfortunes which arose from this miserable harvest because when the wine-growers saw the plants with their frozen grapes, and that day after day the frost deepened/intensified, without any hope of reaching maturity, they decided to harvest the grapes as they were. Once collected, they brought them in bags to their homes and unfroze them as they could in stoves or other warm places.

With the help of winepresses they extracted all the possible must and put it in their barrels. After all their troubles, the wine that was produced had a certain bitterness and harshness. However, it was marvelous/wonderful how well it matured in the barrels and that in the next summer it was delicious and sweet to drink. Although I have already described in length how infertile this year was, I must yet briefly mention that the plants which were sown in the gardens did not grow at all. The apples and pears did not reach their usual size and did not have such a taste as the other years. Therefore, this miserable year, as long as it lasted, was devoid of all good fruits. […] The next year (1259) was so temperate and well-disposed that by its fertility it contented mankind so much that they could forget about the infertility of the previous years.

3. How reliable are the GHD recovered for the 13th century?

Written sources can contain some dating inaccuracy, some errors and even some forgeries. That's the reason why they always need to be carefully analyzed in order to assess their reliability (Bell and Ogilvie, 1978; Ogilvie and Farmer, 1997). The 1258 grape harvest dates were obtained from two well-informed and contemporary sources:

1) Annales Clerici Parisiensis: This original manuscript (Cotton MS Vespasian D IV, ff 66v-72r, Figure 3) of this text can be found in the British Library, after the chronicles written by Guillaume le Breton (1165-1226) and Vincent de Beauvais (1184/94-1264). Although the identity of the author of the *Annales Clerici Parisiensis* still remains unknown, as it is often the case with mediaeval authors (Bell and Ogilvie, 1978), we know that the chronicler was a cleric from Paris and that he was a direct witness of the cold conditions experienced during the summer and autumn 1258 since the chronicle was written between 1249 and 1269 (Waitz, 1882, in MGH: 26; Alexandre 1987). In 1877, Leopold Delisle was the first to draw the attention of French historians on the usefulness and accuracy of the information provided by this account (Delisle, 1877). The climate historian Pierre Alexandre also confirmed that the weather references found in this source were original and reliable (Alexandre, 1987).

2) Chronicle of Richer of Senones. The original manuscript of this source can be found in the French National Library (MS Latin 10016, BNF, Paris). Along with the chronicle written by Matthew Paris, the work by Richer of Senones (Lorraine-Alsace region, France) is probably one of the longest and most detailed testimonies referring to the climate anomalies observed during the summer and fall 1258. The author of the source is well known by historians. Richer of Senones was born around 1190 and died in 1266. He became monk at Senones abbey were he started to write his Chronicle. The manuscript was written between 1250 and 1266, indicating that Richer witnessed himself the climatic anomalies he recounts for the year 1258.

The cold weather conditions and the late harvest reported by the *Annales Clerici Parisiensis* and the Chronicle of Richer of Senones during the fall of 1258 are further confirmed by two additional written sources:

1) *Annales Argentinenses Fratrum Praedicatorum*. The Annals of friars of the order of preachers of Strasbourg (eastern part of France) were written between 1252 and 1261 by a monk whose identity is unknown. We selected this text as the description of the vineyards affected by frost during the autumn of 1258 is in excellent agreement with the descriptions, found in the Chronicle of Richer of Senones and the *Annales Clerci Parisiensis*:

1258 Anno Domini MCCLVIII. Tanta fuit aeris intemperies, quod annona computrivit in terra, et botri crudi et immaturi remanserunt, ita quod tempore vindemiarum gelu superveniente in sportis et in saccis inferebantur et in torcularibus cum calciis calcabantur, et effluxit glacies cum vino. Sequenti autem anno crevit optimum vinum.

Annales Marbacenses qui dicuntur – Annales Argentinenses Fratrum Praedicatorum, BLOCH H. (ed.), 1907. Scriptores Rerum Germanicarum, Vol. 9, Hanover and Leipzig, pp. 124-133.

Translation : *Year of the Lord 1258. There was such bad weather that the crops rotted in the ground and the grapes remained green and did not ripen. Frost occurred at grape harvest time and while the grapes were collected and crushed, wine mixed with ice flowed from the winepresses. The following year gave an excellent wine.*

2) *Annales S. Martialis Lemovicensis*. The annals of Saint Martial of Limoges (West-central France) were written in the 13^{th} century by an anonymous author. The annals state that the winepresses were still in activity in late November 1258, suggesting that the grapes harvest didn't probably start before the end of October or the beginning of November. We here provide the original text and the following translation:

1257[4] *M.CC.LVII. Tantae fuerunt pluviae in regno Francia, sicut alibi scripsi, quod nec segetes nec vina potuerunt maturari. Duas saumatas agrestae vidi hic pro vino reddi. In festo sanctae Katerinae [torcular Sancti Martini adhuc vindemia tali occupatum]. Plures etiam fuerunt qui non collegerunt tales vindemias, immo dimiserunt in vineis. Tanta viriditas fuit [tunc in vino Lemovicis et circa quod non poterant bullire in vasis vina, sed in Martio sequenti videbantur bullire]. Vinum vetus vendebatur tunc Lemovicis VII. solidis et plus et parum minus. Anno sequenti, fuit penuria bladi ; in mense Januarii vendebatur sextarium siliginis VIII. solidis; sextarium frumenti IX sliginis ; [sextarium vini, XVI. denariis ante messes post X. solidis; sextarium siliginis et sextarium frumenti, X solidis et plus.] Et durabat ista penuria per totam Acquitaniam et per plura alia loca.*

Majoris chronici Lemovicensis quintum supplementum de pretiis annonae, GUIGNIAUT J.D., DE WAILLY N. (eds.), 1855. Recueil des historiens des Gaules et de la France, Vol. 21, Imprimerie Impériale, Paris, pp. 800-802.

[4] *We here suggest, in agreement with other historians (Duples-Agier, 1874 ; Alexandre 1987), that an error was made when the manuscript was produced and that the wet summer of 1257 in fact refers to the summer of 1258.*

Translation:

So much rain fell on the kingdom of France, as I have already mentioned elsewhere, that neither the crops nor grapes could reach maturity. I saw two saumatas[5] *of grain be exchanged against wine. During the feast day of Saint Catherine (25th of November), the winepress of Saint Martin was still in activity. Numerous were those that could not collect enough grapes during harvest time and instead abandoned their vineyards. At this time the must produced in Limoges and in the surrounding areas was so full of green, unripe grapes that it could not ferment and it is only in March of the following year that it started to ferment. The wine from preceding years was sold at least 7 shillings in Limoges. The following year, there was a great shortage of grain; in the month of January, the setier*[6] *of rye was sold 8 shillings, the setier of wheat 9 shillings; the setier of wine was sold 16 deniers before the harvest and after 10 shillings; the setier of rye and of wheat 10 shillings and even more. This shortage lasted in all Aquitaine and in many other places.*

[5] *The saumata was a unit of quantity. It was roughly equivalent to the amount that a mule ("bête de somme") could carry.*

[6] *The setier was a French measurement for liquids and dry products. The value of a setier was not fixed and extremely variable for one place to another. For cereals the setier varied between 150 and 300 litres. The Parisian wine setier contained 7.45 litres.*

Text S3. Statistical analyses performed on the GHD series.

Methods

The three analyzed GHD series show very similar year-to year fluctuations, indicating that they more or less capture the same (climatic) signal. Based on this similarity, missing values were imputed for all years for which at least one observation was available. This lead 3 series of 623 GHDs, among which 11 years were recognized as the specific sample of "volcanic years" during which major known eruptions occurred, potentially perturbation (cooling) the natural climate variability.

For all three series, and both with and without volcanic years within the analyzed sample, extreme GHD were selected as the 10% latest dates (frequent assumption for over-threshold modelling, Coles 2001). In addition, to summarize the information conveyed by the three series, a fourth one, later on denoted as "composite", was defined as the median of the different threshold exceedences if different series exceed their respective threshold simultaneously, and as the sole exceedence if only one exceedence actually occurred a given year. This was also done with and without volcanic years, leading in fine 8 samples of extreme GHDs.

The 8 samples were fitted using the discrete version of the Generalized Pareto Distribution (GPD). This was done instead of using the more classical continuous GPD (which was used for determining the return period associated with the lowest temperatures retrieved from tree rings) because of the discrete nature of GHDs. Note that statistical extreme value theory ensures, in the continuous case, convergence of exceedences above high thresholds to the GPD under rather mild assumptions (Pickands, 1975). Also still not so strongly justified in the discrete case, some results now suggest that the discrete GPD is arguably the most sensible choice for discrete extreme data (Dkengne Sielenou et al., 2016). The fitted distributions were, in fine, used to determine the return period of the 1258 GHD, as well as of other volcanic years.

Results

All analyses agree to the very exceptional nature of the 1258 GHDs. With the 11 volcanic years within the GPD fitting samples, i.e. assuming that these contribute to defining the natural climate variability, the 1258 return period is estimated to ~2000-3500 years, with rather coherent values from one series to another. When the 11 volcanic years are removed from the GPD fitting, the result is even more spectacular, with infinite or close to infinite estimates for the 1258 GHD return period for the four series (Table 1). This suggests that GHD as late in the year as the 1258 ones are simply not possible in the analyzed areas under the natural unperturbed climate variability. As a comparison, return periods of GHDs corresponding to three other major volcanic years and estimated from the same distributions (i.e. with the 11 volcanic years not in the fitting sample) and for the composite series range from rather ordinary (1809) to high (1816), but with values indicating that one stays always within or close to conditions corresponding to non-volcanic years.

With volcanic years in the GPD fitting				Without volcanic years in the GPD fitting			
Alsace	Ile de France	Burgundy	Composite series	Alsace	Ile de France	Burgundy	Composite series
2641	3618	3163	1988	981,562	Inf.	Inf.	553,594

Table 1. Return period (in years) of the 1258 GHD according to the different modelled series

Year	Number of days above threshold	Return Period (years)
1258	21	553,594
1695	7	39
1809	4	16
1816	17	765

Table 2. Return period of GHD corresponding to main volcanic years for the composite series, with volcanic years removed from the discrete GDP fitting. For volcanic years different of the four in the table, the composite series does not exceed its selected threshold, indicating an ordinary GHD.

Text S4. New evidence of a widespread dust veil over Europe following the Samalas eruption.

Introduction

Only a few texts describing volcanic dust veils or dry fogs (i.e, unusual optical phenomena induced by the presence of volcanic aerosols into the stratosphere or troposphere - dimming of the Sun, haze, dark total lunar eclipse, Bishop's rings) have been preserved over the past millennium.

They are particularly abundant for the 1783 Laki (*Stothers, 1993; Demarée et al., 1999; Thordarson et al., 2003*), 1883 Krakatoa eruption (*Flammarion, 1885; Symons, 1888*) and to a lesser extent for the 1816 Tambora event (Stothers, 1984b) but tend to become sparse as we go back in time, the only exception being the 536 event for which four reliable contemporary description of the sky conditions in 536/537 have been discovered (Stothers, 1984a).

Dust veil reports are especially rare for the 1257 Samalas eruption. The only descriptions ever published were recovered 16 years ago by Richard Stothers (2000). Here we shed the light on historical material recently discovered attesting the presence of a widespread dry fog over Western Europe.

Munkeliar

We here provide the reader with the original Latin as well as the information needed to get access to original source:

Speyer (Germany):

1258 Eodem eciam anno maxima fuit corrupcio vini et frumenti et aliarum frugum et appellatus est annus idem a vulgo munkeliar.

Annales Spirenses, PERTZ G.H., 1861. Monumenta Germaniae Historica, Scriptores 17, Hanover, pp. 80-85.

Translation:

The same year, wine, wheat and other fruits were greatly altered and this year was also commonly referred to as munkeliar.

When the Annals of Speyer were first edited in 1861 in the Monumenta Germaniae Historica (MGH), the editor Georg Heinrich Pertz translated in Latin the term *munkeliar* as *annus obscuritatis* (dark year) or *annus caliginis* (year of fog). The Latin translation was provided in an extremely brief footnote that the reader can read in the volume 17 of the MGH, page 85.

G.H. Pertz never explained the reasons that led him to translate Munkeliar as *annus obscuritatis* or *annus caliginis*. In our opinion, *munkeliar* can be decomposed in two parts: *munkel* and *iar*. *munkel* now refers to the German word *dunkel*, an adjective meaning *dark* while *iar* refers to the German noun *Jahr*, meaning year.

The dark total lunar eclipse of the 12 November 1258

1. Lunar eclipse: a brief definition

An eclipse of the Moon occurs at Full Moon when the Moon passes through some portion of Earth's shadow. The shadow of the Earth can be divided into two distinctive parts: the umbra and penumbra. The umbral shadow is a region where the Earth blocks *all* direct sunlight from reaching the Moon. The penumbral shadow is a zone where the Earth blocks part but not all of the Sun's rays from reaching the Moon.

Three types of lunar eclipses have been defined by astronomers:

- Penumbral eclipse occurs when the Moon passes through Earth's penumbral shadow
- Partial eclipse occurs when a portion of the Moon passes through Earth's umbral shadow
- Total eclipse occurs when the entire Moon passes through Earth's umbral shadow. All total eclipses start with a penumbral followed by a partial eclipse, and end with a partial followed by a penumbral eclipse.

2. Lunar eclipses: A tool to detect the presence of volcanic aerosols in the stratosphere

During a total lunar eclipse, white sunlight hitting the atmosphere on the sides of the Earth is absorbed and then scattered. Blue-colored light is most affected while most of the orange or red-colored light passes through the Earth's atmosphere without being absorbed and scattered. The remaining light is then refracted by the Earth's atmosphere into the Earth shadow, projecting indirect, reddish light onto the Moon. This explains why usually the eclipsed-Moon tends to exhibit a reddish color. However, when the stratosphere contains a large amount of volcanic aerosols the sunlight can no longer be refracted and scattered into the Earth shadow and the Moon tends to become darker. In extreme cases, it can also vanish completely and become invisible (Stothers, 2004).

Numerous papers (Keen, 1983; Stothers, 2000; Hofmann et al., 2003) have shown that the study of the brightness of lunar eclipses can be a useful tool to detect the presence of volcanic aerosols into the stratosphere and to measure the optical depth of the stratosphere following large volcanic eruptions. Most of the dark lunar eclipses since 1600 have been linked to large volcanic eruptions (Keen, 1983).

Richard Stothers (2000) identified in the Bury Saint Edmunds Abbey chronicle written by John of Taxster in England as an account referring to an unusually dark lunar eclipse on the 18 May 1258, which was attributed to presence volcanic materials into the stratosphere.

We discovered in the *Annales Ianuenses* (1249-1264CE), written in Genoa (Italy), a new account describing an unusually dark lunar eclipse on the 12th November 1258. This text can be considered as one of the most detailed description of a lunar eclipse we have for the 13th century and possibly for the whole mediaeval period. Here, we present here the original text written in Latin and the ensuing translation:

Eodem anno nocte .XII. Novembris luna existens XVI. cum iam hora esset.............., ex toto disparuit; quod qui non viderunt eam, credebant ipsam nondum ortam, nec credebant illis, qui viderunt eam, cum nullum vestigium appareret ubi fuisset vel esse deberet quamvis tempus esset serenissimum, et cimerium lune deberet esse in loco, in quo est sol in estate quando est hora plus quam tercia, cepit ibi apparere subtillisima, sicut subtilior fuit unquam, et paulatim crescens ad statum consuetum devenit.

Unde versus:
Undecies quinque iunctis numeris cum mille ducentis
Et tribus annexis duodecima nocte Novembris,
Cum sine nube fuit celum nituitque serenum,
Luna diu latitans, cum debuit esse rotunda,
Visibus humanis se totam [subtrahit atra]
Post moram suam longa denua cornua pandens
Paulatim crevit et perdita lumina sumpsit.

Annales Ianuenses (1249-1264), PERTZ G. H. (ed.), 1863. M.G.H. SS 18, 1863, Hanover, pp. 226-248.

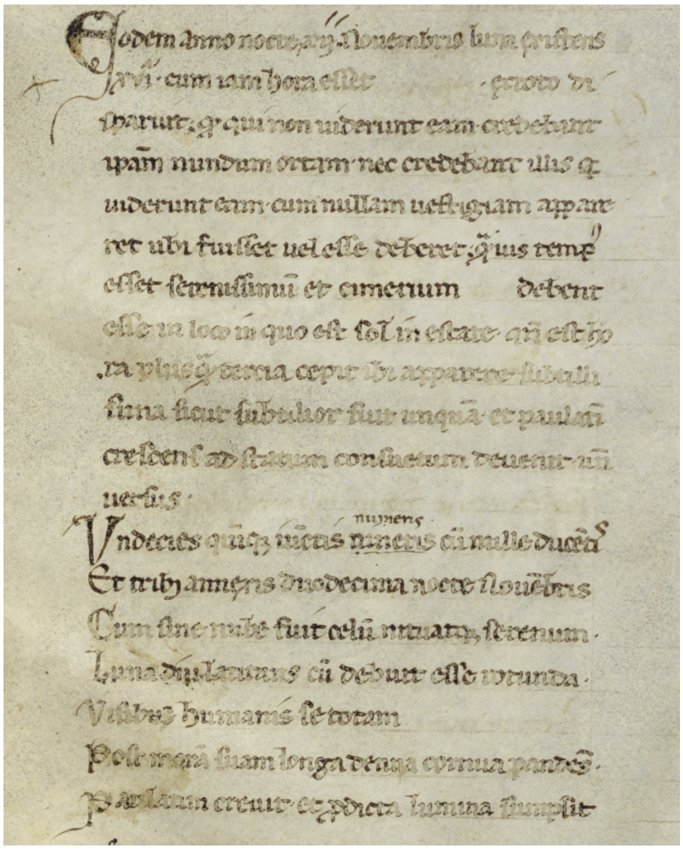


Figure 5. Annals of Genoa by Cafaro (1100-1300), Paris, BnF, département des manuscrits, Latin 10136, fol. 170v.

Translation:

The same year, on the night of November 12th, the moon appeared at the 16th hour ....[7], then it disappeared completely. Those who did not see it thought it had not risen yet, they did not believe those who had seen it because no trace appeared at the spot where it was supposed to be found, despite clear weather conditions. Then the top of the moon, which was at the same position as the sun in summer when it is more than the third hour, began, as never before, to be clearly visible, and little by little the moon resumed its normal appearance.

Hence the following verse:
The night of November 12, 1258,
While the sky was clear, cloudless and bright,
The moon remained hidden for a long time, whereas it should have been full
Dark, it withdrew entirely from the vision of men,
After a delay, the Moon unveiled its long horns again
Gradually it grew and recovered the full light it had lost.

[7] *Blank space in the original manuscript.*

3. Assessing the reliability of the *Annales Ianuenses*

This testament raises several important questions. Is the date of occurrence of this total lunar eclipse correct? Did two eclipses really occur in 1258? Are the information provided by the Annals of Genoa accurate and reliable?

In order to categorize a source as reliable, it must fulfill certain criteria; in particular it has to be written close in time and space to the events described. Knowing who the author was can also help judging the authenticity of a source (Ogilvie et al., 2010).

The Genoese annals were begun in 1100CE by Caffaro di Rustico. After his death in 1163, his work was continued by others chroniclers at the request of the city of Genoa until 1294. Little is known about the chronicler who wrote the section from 1249 to 1264. But we do know he was specifically appointed by the government of Genoa to write the official history of the city and that he was contemporaneous with the events he relates. Furthermore such a precise, thorough description strongly suggests that the writer witnessed the eclipse he depicts, thus adding confidence that this source should be regarded as reliable.

But to further assess the validity of this testimony and make sure that the date of occurrence of the eclipse given by the chronicler is correct, we employed the *Five millennium catalogue of Lunar eclipses* (Espenak and Meeus, 2009). This catalog is the first to provide visibility maps for every lunar eclipse (12064 eclipses) over a period covering five thousand years from –1999BCE to +3000CE. It was mainly intended to "assist historians and archeologists in the identification and dating of lunar eclipses found in references and records from Antiquity" (Espenak and Meeus, 2009).

In addition, we also used the Lunar eclipse program (LUNECJM) developed by Jean Meeus (http://eclipse.gsfc.nasa.gov/JLEX/LUNECJM.html) which allows the determination of whether a particular eclipse was visible for any location on earth. It also provides information about the start, end times and duration of each phase of an eclipse (penumbral, partial and total).

Figure 6 confirms that two total lunar eclipses did occur in 1258. The first one occured in the 18th of May while the second happened seven months later on the 12th of November. Both of them were visible in Europe and the dates provided by the Espenak and Meeus (2009) match perfectly with the dates recorded by John of Taxster in the Bury Saint Edmunds chronicle (Stothers. 2000) and the chronicler from Genoa.

The outputs from LUNECJM (Table 3) indicate that the eclipse of the moon of the 12 November 1258 was only partially visible in Genoa. The first phase of the eclipse (penumbral phase, i.e, the entrance of the moon into the penumbral shadow) was not visible as the moon was below the horizon. However, the fact that contemporary observers could not observe the penumbral eclipse is not critical as these events are not used to detect the presence of volcanic aerosols in the stratosphere (Stothers, 2004). The only reliable indicator that can be used to assess the state of the stratosphere (transparency or high turbidity) are accounts describing the totality.

Table 1 indicates that, except for the penumbral eclipse, all the other phases of the eclipse, including the most important one – the totality -, were visible in Genoa, thus adding credibility to the report written by the chronicler of the *Annales Ianuenses*.

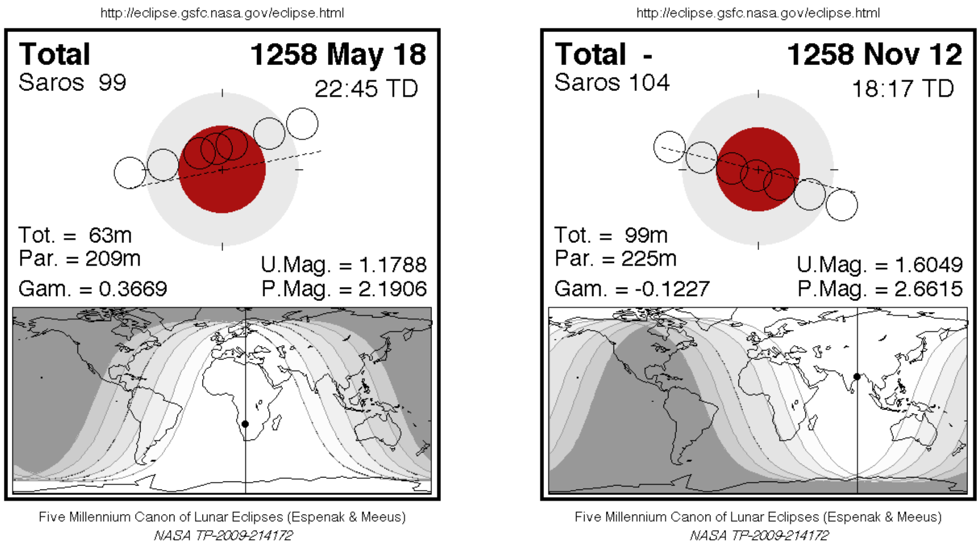


Figure 6. The dark total lunar eclipses of the 18 May and 12 November 1258: Visibility maps (Source: Espenak and Meeus, 2009)

Date	Eclipse Type	Penumbral Magnitude	Umbral Magnitude	Penumbral Eclipse Begins[8]	Partial Eclipse Begins	Total Eclipse Begins	Middle Eclipse	Total Eclipse Ends	Partial Eclipse Ends	Penumbral Eclipse Ends
1258-Nov-12	Total	2.661	1.605	*16:09*[9]	17:15	18:18	19:07	19:57	21:00	22:05

Table 3. Outputs from LUNECJM. The dark total lunar eclipse of the 12 November 1258: Start and end times in Genoa, Italy.
Latitude: 44° 25' 00" N, Longitude: 8° 57' 00" E, Altitude: 96.9m, Time Zone: 01:00 E.

[8] *All times are displayed in local time.*
[9] *Events shown in gray occurred below the horizon and were not visible.*

4. Evaluating the brightness of the moon in mediaeval records: The Danjon scale

The French astronomer André Danjon (Danjon, 1921) proposed a four-point scale for evaluating the visual appearance and brightness of the Moon during total lunar eclipses. 'L' values for various luminosities are defined as follows:

Danjon Scale	
L =	
L = 0	*Very dark eclipse. Moon almost invisible, especially at mid-totality.*
L = 1	*Dark Eclipse, gray or brownish in coloration. Details distinguishable only with difficulty.*
L = 2	*Deep red or rust-colored eclipse. Very dark central shadow, while outer edge of umbra is relatively bright.*
L = 3	*Brick-red eclipse. Umbral shadow usually has a bright or yellow rim.*
L = 4	*Very bright copper-red or orange eclipse. Umbral shadow has a bluish, very bright rim.*

Table 4. Danjon Scale of Lunar eclipse brightness

We used the Danjon scale (Table 4) to categorize the moon color and brightness during the lunar eclipse of the 12th November 1258. This scale has been specifically designed to estimate the brightness of the Moon with the naked eye, which is perfect for our purpose as no binoculars or telescopes existed in the 13th century.

The *annales Ianuenses* state at two places in the manuscript that the moon was almost completely invisible during the phase of the totality. The chronicler also stresses that the weather conditions were good, which indicate that the complete disappearance of the moon cannot be explained by the presence of clouds preventing the observer from seeing clearly the eclipse. All these elements lead us to suggest that the lunar eclipse that occured in Genoa on the night of the 12 November 1258 should be rated 0 on the Danjon scale and that the unusual appearance/darkening of the moon was very likely caused by aerosols still suspended in the atmosphere about 1.5 years after the Samalas eruption.

The description found in the annals of Genoa shares several common features with the reports made 558 years later by astronomers who observed the moon eclipse of the 9 June 1816. This lunar eclipse occurred 15 months after the Tambora eruption and has been rated 0 on the Danjon scale (Stothers, 2005). The unusual darkness of the eclipsed-moon during its totality on the night of the 9 June 1816 strickened contemporary astronomers as illustrated by the following accounts (Figure 7):

A)

To the Editor of the Monthly Magazine.

SIR,

HEREWITH you have an account of the late eclipse, as observed here.

Ipswich.—Eclipse of the Moon,
June 9, 1816.

Penumbra near to contact . . 11h. 23′

Eclipse *commenced* . 11 28 Diff. 2′— from calcul. at *Greenwich.*

☽ half eclipsed . 12h. 0′

Appears as about four days old . . . 12 12

Wholly obscured by the full shadow . 12 43 Diff. 4′+ from calcul. at *Greenwich.*

Total darkness still continues . . . 13 36 = 1. 36 civil time.

Emersion obscure . 51 Diff. 30″—

Emersion clear and considerable . . 14 5 = 2. 5

☽ beautiful as of two days old . . . 14 8 = 2. 8 civil time.

Beautifully crescent and sharp, the full shadow and penumbra clearly conspicuous, and well terminated on the disc 14 38 = 2. 38

Emersion

page 2

1816.] *Accounts of the la*

Emersion complete—
end of the eclipse 14.57 = 2.57. Duration 3h. 29′. Diff. 3¾ minus.

The equation of time, about 1min. 5″ to be deducted.

Observations.—Just before the eclipse became total, the Moon appeared like a dim star of the 2d, and then of the 5th, magnitude.

A star was seen south of her as in apparent contact nearly with the obscured disc.

Another, farther from her, to the eastward, and the Herschelian planet, became discernible.

Usually the Moon in a total eclipse does not disappear, but is seen as of a faintish red through the shadow. In this instance the shadow, which passed before her, was so dense, that she totally disappeared.

Viewed, except the *emersion*, with the night glass, but that with the pocket *Dollond*, and the *Dollond* large *refractor.*

page 3

B)

XV. *Observations made at Bushey Heath (North Latitude* 51° 37′ 44″,3; *West Longitude, in time, from Greenwich,* 0ʰ 1ᵐ 20ˢ,93), *from May* 17, 1816, *to December* 7, 1824. *By Colonel* BEAUFOY, *F.R.S. Communicated in a Letter to* FRANCIS BAILY, *Esq., President of the Society.*

Read April 8, 1825.

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II. Eclipses of the Sun, Moon, &c.

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				Apparent time. h	m	s
1816.	June 9.	Lunar Eclipse				
		Beginning of the eclipse		11	30	30
		Beginning of total darkness		12	49	22
		End of total darkness		13	43	50
		End of the eclipse		14	58	44
		N.B. The Moon totally disappeared.				
				Mean time.		
1818.	Apr. 20.	Lunar Eclipse	End	13	28	47
	May 4.	Solar Eclipse	Beginning	17	53	55
			End	19	41	17
	Oct. 13.	Lunar Eclipse	Beginning	16	41	20
1820.	Mar. 29.	Lunar Eclipse	End	8	09	09
		N.B. The moon rose eclipsed.				

Figure 7. Accounts reporting the occurrence of a dark total lunar eclipse on the night of the 9 June 1816. A) Observations made in 1816 at Ipswich (England) by Capel Lofft and published in the Monthly Magazine, (Source: Lofft C., 1816. The Monthly Magazine, vol. 42, pp 2-3). B) Observations made in 1816 at Bushey Heath (England) by Colonel Mark Beaufoy and published in the Memoirs of the Astronomical Society of London, (Source: Beaufoy M., 1826. Memoirs of the Astronomical Society of London, vol. 2, pp 129-135).

Table S2. Tree-ring chronologies used in this study for the reconstruction of Northern hemisphere (NH) JJA temperature anomalies for the period 1000–2000.

ID	Cluster name	Proxy	Tree ring chronologies	Country	Latitude	Longitude	Species	Parameter	Chronology type	Period	References
1	Alaska - Northern Canada	Tree ring	Firth River	United States	68.8	-142.4	*Picea glauca* (Moench) Voss	*MXD*	*SF-RCS*	1073-2002	*Anchukaitis et al., 2013*
		Tree ring	Seward Composite	United States	65.16	-162.25	*Picea glauca* (Moench) Voss	*TRW*	*STD*	978-2002	*D'Arrigo et al., 2006*
		Tree ring	Coastal Alaska (GOA)	United States	60.5	-146	*Tsuga mertensiana* (Bong.) Carrière	*TRW*	*RCS*	713-2003	*D'Arrigo et al., 2006*
		Tree ring	Campbell Dolomites B	Canada	68.3	-133.3	*Picea glauca* (Moench) Voss	*MXD*	*RCS*	1175-1992	*Schweingruber, ITRDB; Schneider et al., 2015*
2	British Columbia	Tree ring	Athabasca - Icefields	Canada	52.3	-117.3	*Picea engelmannii*	*MXD*	*RCS*	1072-1994	*Luckman et al., 2005*
		Tree ring	Coastal British Columbia (CWD)	Canada	52	-126	*Tsuga mertensiana* (Bong.) Carrière	*TRW*	*STD*	1094-2010	*Pitman et al., 2012*
3	Quebec	Tree ring	Quebec - Strec	Canada	57.3	-74	*Picea mariana* (Mill.) B.S.P	*TRW*	*RCS*	910-2011	*Gennaretti et al., 2014*
4	Western Europe	Tree ring	French Alps - Composite (Merveilles - Nevache Granges - Fressinière Grand-Bois)	France	44	7	*Larix decidua* Mill.	*TRW*	*SF-RCS*	751-2007	*Corona et al., 2010; This study*
		Tree ring	Lauenen	Switzerland	46.4	7.3	*Picea abies (L.)* H. Karst	*MXD*	*RCS*	982-1976	*Schweingruber et al., 1988*
		Tree ring	Lötschental	Switzerland	47.5	7.5	*Larix decidua* Mill.	*MXD*	*RCS*	735-2004	*Büntgen et al., 2006*
		Tree ring	Tyrol	Austria	47.5	12.5	*Picea abies (L.)* H. Karst	*MXD*	*RCS*	1047-2003	*Esper et al., 2007*
		Tree ring	Pyrenees	Spain	42.5	2.5	*Pinus uncinata* Ram	*MXD*	*RCS*	1044-2005	*Büntgen et al., 2008*
5	Central Europe	Tree ring	Tatra	Slovakia	48-49	19-20	*Larix decidua* Mill.	*TRW*	*RCS*	963-2011	*Buntgen et al., 2013*
6	Scandinavia	Tree ring	Nscan	Finland-Sweden	67.5	22.5	*Pinus silvestris*	*MXD*	*RCS*	-181- 2006	*Esper et al., 2012*
		Tree ring	Torneträsk	Sweden	68.2	19.7	*Pinus silvestris*	*MXD*	*RCS*	441-2010	*Melvin et al., 2013*
		Tree ring	Jämtland	Sweden	63.5	15.5	*Pinus silvestris, Picea abies (L.)* H. Karst	*MXD*	*RCS*	1111-1978	*Schweingruber et al., 1988; Schneider et al., 2015*
		Tree ring	Forfjorddalen 2	Norway	68.8	15.73	*Pinus silvestris*	*TRW*	*STD*	877-1994	*Kirchhefer et al., 2000*
7	Siberia - Polar Ural	Tree ring	Polar Ural	Russia	66.9	65.6	*Larix sibirica* Ledeb, *Picea obovata* Ledeb	*MXD*	*SF-RCS*	778-2006	*Briffa et al., 2013*
		Tree ring	Yamal	Russia	67.32	69.54	*Larix sibirica* Ledeb	TRW	SF-RCS	-764-2005	*Briffa et al., 2013*
8	Siberia - Taymyr	Tree ring	Taymyr	Russia	72	102	*Larix gmelinii* Rupr.	TRW	RCS	-207-2003	*Naurzbaev et al., 2002 ; Briffa et al., 2008; Sidorova et al., 2010*
9	Siberia Yakutia	Tree ring	Indigirka - Yakutia	Russia	69-70	148-149	*Larix cajanderi* Mayr.	TRW	RCS	-929-2004	*Sidorova and Nauzbaerv, 2002; Sidorova 2003; Hughes et al., (in preparation)*
10	Central Asia Altai - Mongolia	Tree ring	Altai	Russia	50	88	*Larix sibirica* Ledeb	TRW	RCS	-359-2011	*Myglan et al., 2012*
		Tree ring	Altai	Russia	50	88	*Larix sibirica* Ledeb	MXD	RCS	556-2007	*Schneider et al., 2015*
		Tree ring	OZN	Mongolia	51.15	99.04	*Larix sibirica* Ledeb	TRW	SF-RCS	931-2005	*Davi et al., 2015*
11	China - Qilian Mountains	Tree ring	Qilian Mountains - HY	China	99.7	38.7	*Sabina przewalskii* Kom., *Picea crassifolia* Kom.	TRW	STD	670-2012	*Zhang et al., 2014*
12	Greenland - Ice Cores	Ice Core	GRIP	Greenland	72.58	37.6	-	d18O	-	552-1973	*Vinther et al., 2010*
		Ice Core	CRETE	Greenland	71.12	37.32	-	d18O	-	552-1973	*Vinther et al., 2010*
		Ice Core	DYE3	Greenland	65.1	43.8	-	d18O	-	552-1973	*Vinther et al., 2010*

Figure S1. Location map of the proxy data used in this study.

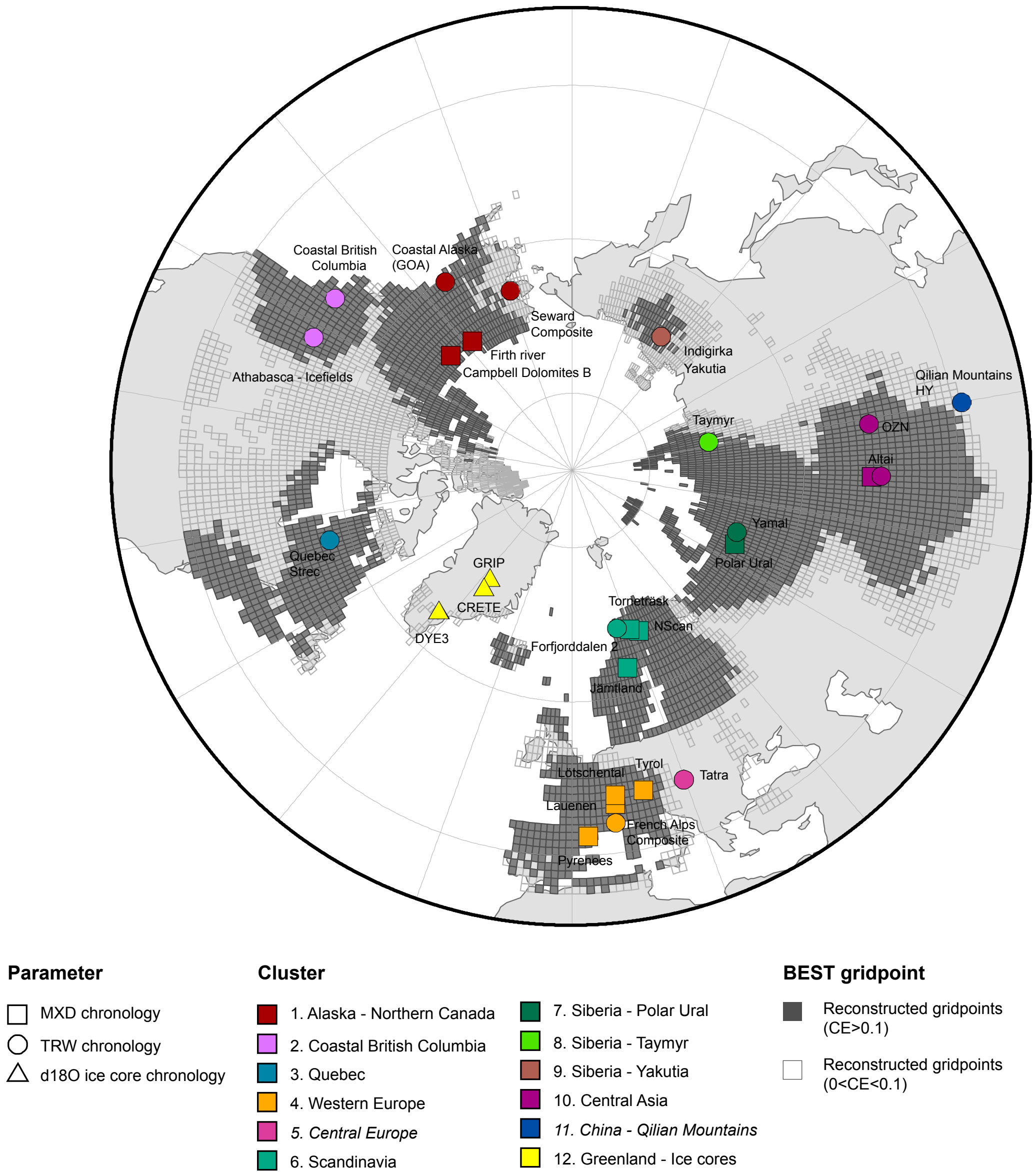


Table S3. Statistics of reconstructed JJA temperature in NH reconstruction for each nest

Nest - Period	996-1044	1044-1047	1047-1073	1073-1111	1111-1140	1140-1170
nchron	17	18	19	20	21	22
p	4	5	5	5	6	5
R^2b	0.39[0.3-0.5]	0.43[0.33-0.53]	0.44[0.3-0.57]	0.42[0.32-0.56]	0.43[0.33-0.54]	0.43[0.33-0.54]
r^2b	0.37[-0.03-0.49]	0.37[0.05-0.49]	0.35[-0.04-0.48]	0.36[-0.03-0.49]	0.38[0.04-0.54]	0.36[-0.02-0.49]
REb	0.38[0.08-0.49]	0.38[0.05-0.5]	0.36[0.04-0.47]	0.36[0.03-0.5]	0.38[0.06-0.53]	0.37[0.06-0.5]
CEb	0.36[-0.05-0.48]	0.36[0.03-0.49]	0.34[-0.06-0.47]	0.35[-0.05-0.48]	0.37[0.03-0.53]	0.35[-0.03-0.48]

Nest - Period	1170-1221	1221-1225	1225-1230	1230-1972	1972-1992	1992-2000
nchron	23	24	25	26	23	19
p	5	3	4	3	3	7
R^2b	0.42[0.33-0.54]	0.4[0.28-0.51]	0.42[0.29-0.53]	0.41[0.3-0.49]	0.41[0.29-0.51]	0.45[0.29-0.57]
r^2b	0.36[0.08-0.47]	0.38[0.15-0.49]	0.36[0.01-0.46]	0.35[0.15-0.48]	0.37[0.09-0.48]	0.37[0.09-0.48]
REb	0.36[0.11-0.47]	0.39[0.14-0.5]	0.36[0.07-0.46]	0.37[0.16-0.48]	0.38[0.1-0.47]	0.38[0.14-0.48]
CEb	0.35[0.06-0.46]	0.37[0.13-0.49]	0.35[-0.01-0.45]	0.34[0.13-0.48]	0.36[0.07-0.47]	0.36[0.07-0.48]

nchron - Number of chronologies

p - Number of principal components

R^2b - Median value of R^2b (1000 boostrap iterations) calculated over the calibration period

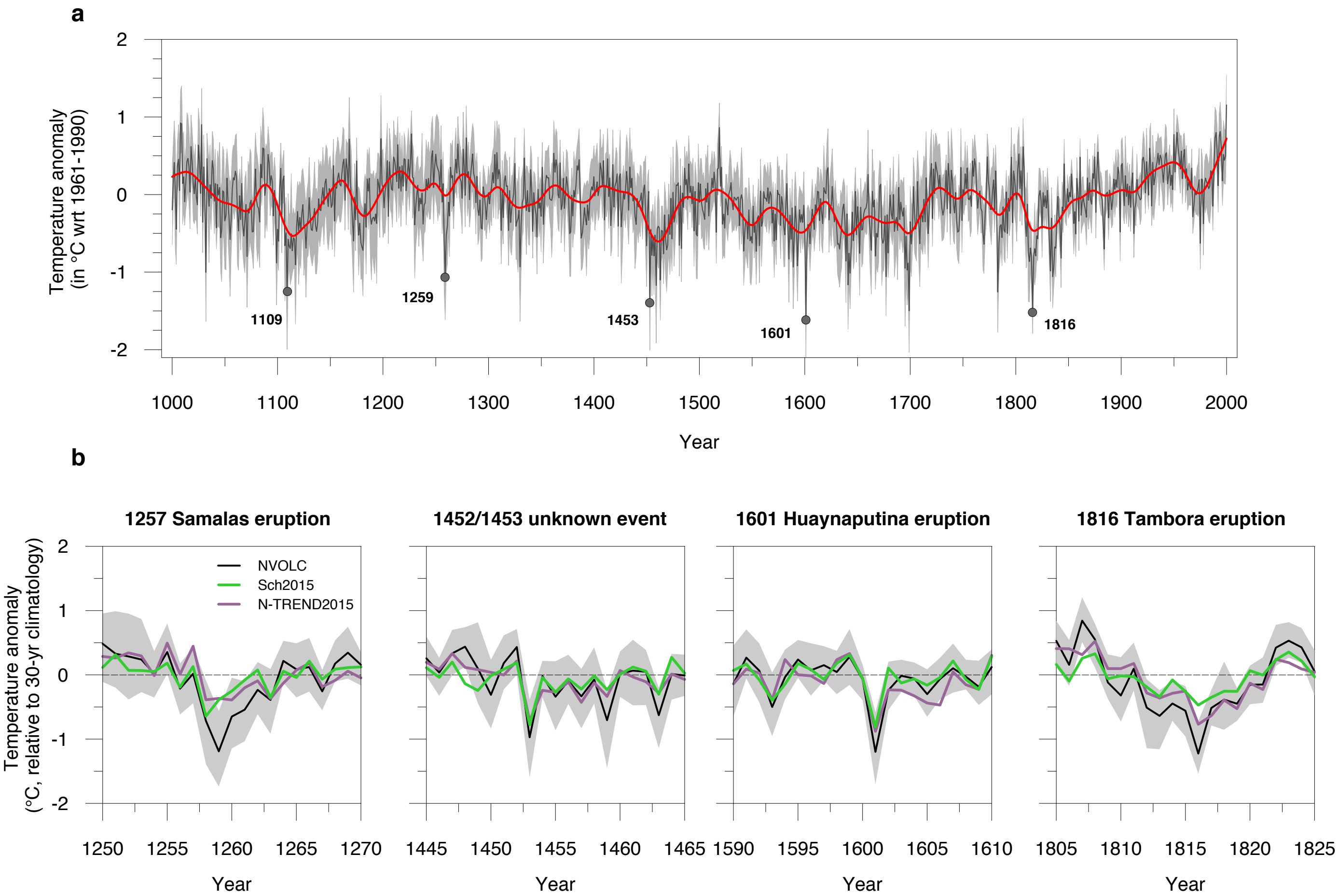
r^2b - Median value of r^2b (1000 boostrap iterations) calculated over the verification period

REb - Median value of REb (Reduction of Error, 1000 boostrap iterations) calculated over the calibration period

CEb - Median value of CEb - Coefficient of Efficiency (1000 boostrap iterations) calculated over the calibration period

Number in brackets refer to the 2.5th and 97.5th percentiles of the R^2b, r^2b, REb, and CEb distributions

Text S5. Comparison of the *NVOLC* reconstruction (panel a) with recently published reconstructions, Sch2015 (Schneider et al., 2015) and N-TREND2015 (Wilson et al., 2016) (panel b).



Panel (a) presents the new *NVOLC* nested reconstruction which is composed of 25 tree-ring chronologies (12 MXD and 13 TRW chronologies) and 3 isotope series from Greenland ice cores. Comparison of this new reconstruction with Sch2015 (Schneider et al., 2015) and N-TREND2015 (Wilson et al., 2016) as illustrated in panel (b) reveals excellent agreement between reconstructions for the 1452/53 "unknown event" and the 1601 Huaynaputina eruption. For the 1257 Samalas and 1815 Tambora eruptions, Sch2015 and N-TREND2015 show a less pronounced cooling, which remains however in the range of uncertainties of the *NVOLC* reconstruction. We explain these discrepancies by

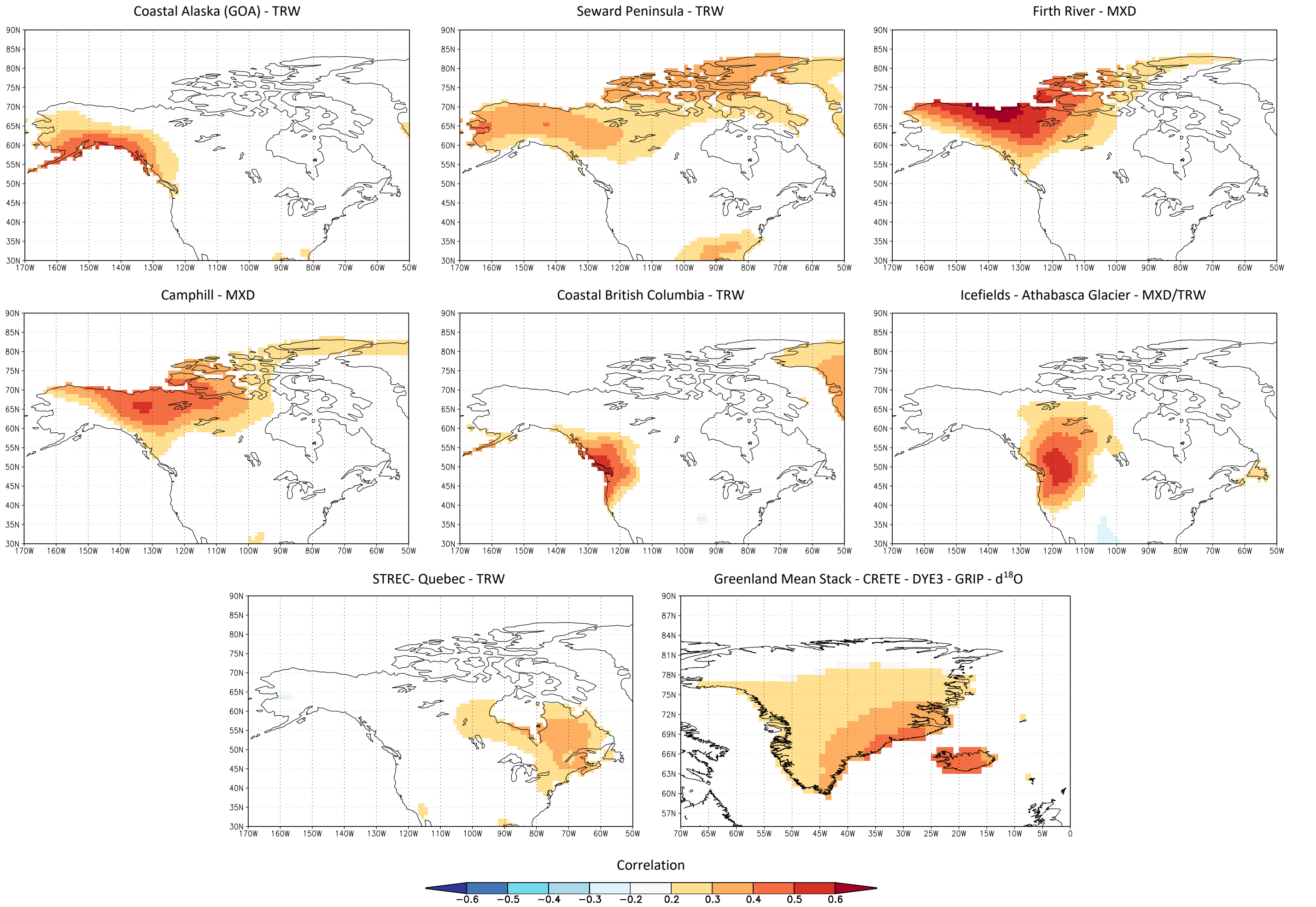
(i) **differences in the tree-ring networks used in the different studies**. Indeed, most of the chronologies we included in *NVOLC* are identical with those used in N-TREND2015 and Schn2015, with some exceptions however. In our study, we included four chronologies which do not appear in the N-TREND2015 network, namely the French Alps, Coastal British Columbia and Indigirka-Yakutia chronologies. The inclusion of the TRW Indirgirka–Yakutia record can be considered as particularly crucial as no other robust chronology, covering this region of the Northern Hemisphere for the period 1257-1260, currently exists. The chronology spans the period 929BC – 2004CE, with a total of 40 trees in the period 1258-1260. The year 1258 stands as the 12th coldest year of the past millennium in the record. In addition to the 3 tree-ring records previously mentioned, we complemented our tree-ring network with 3 annually resolved, summer stable isotope series from Greenland ice cores (GRIP, Crete, DYE3). *NVOLC* was mainly intended to better capture the 1257 volcanic signal. The record presented here only includes chronologies which encompass the full period between today and the 13th century, which is yet another difference to Sch2015 and N-TREND2015 where shorter series have been included as well. We have also limited the selection of chronologies exclusively to series with a clear and unambiguous response to NH summer (JJA) temperatures. "Mixed" gridpoint reconstructions derived from RW and MXD chronologies, available for Asia from Cook et al. (2012) and included in the N-TREND2015 reconstruction, have been excluded on purpose, as some of the gridpoint reconstructions incorporate tree-ring chronologies that that have been used to develop the Monsoon Asia Drought Atlas (Cook et al., 2010; Cook et al., 2012)

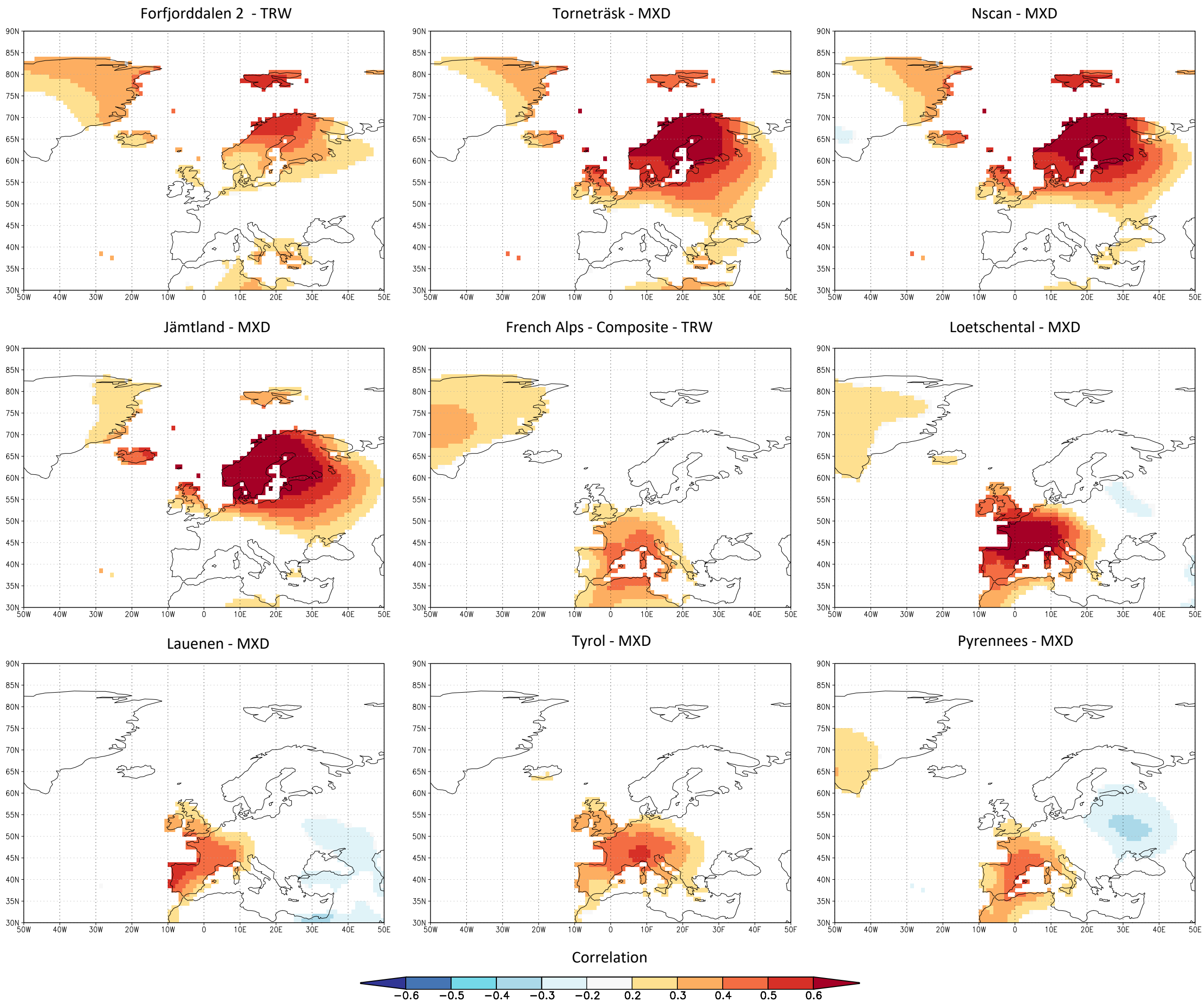
(ii) **the transfer function used to develop the reconstructions**. *NVOLC* is based on a nested principal component regression - to gradually adjust to a changing number of available proxy records (Ortega et al., 2015, Stoffel et al., 2015) – combined with a 1,000 iteration bootstrap approach enabling calculation of uncertainties associated with the reconstruction. By contrast, Sch2015 and N-TREND2015 are based on a scaling approach.

(iii) **the meteorological datasets used for calibration**. *NVOLC* uses monthly mean (1805-1972) JJA temperature anomalies (40-90° N) from the recently released Berkeley Earth Surface Temperature (BEST) dataset (Rohde et al., 2013). Schneider et al. (2015) calibrated their proxy records against monthly mean JJA temperature anomalies (1901-1976) derived from the 5x5° CRUTEM4v network (30°-90° N; Jones et al., 2012). Wilson et al. (2016) scaled their proxy record to CRUTEM4v (40- 75°N) MJJA land temperatures over the 1880-1988 period.

The combination of all these differences in tree-ring networks, transfer functions, meteorological datasets, calibration periods as well as target season likely explain the differences observed in the cooling magnitudes for specific events.

Figure S2. Correlation map between proxy data and JJA gridded temperatures (BEST: 1901:1972, p<10%).




Forfjorddalen 2 - TRW
Torneträsk - MXD
Nscan - MXD
Jämtland - MXD
French Alps - Composite - TRW
Loetschental - MXD
Lauenen - MXD
Tyrol - MXD
Pyrennees - MXD
Correlation
−0.6
−0.5
−0.4
−0.3
−0.2
0.2
0.3
0.4
0.5
0.6

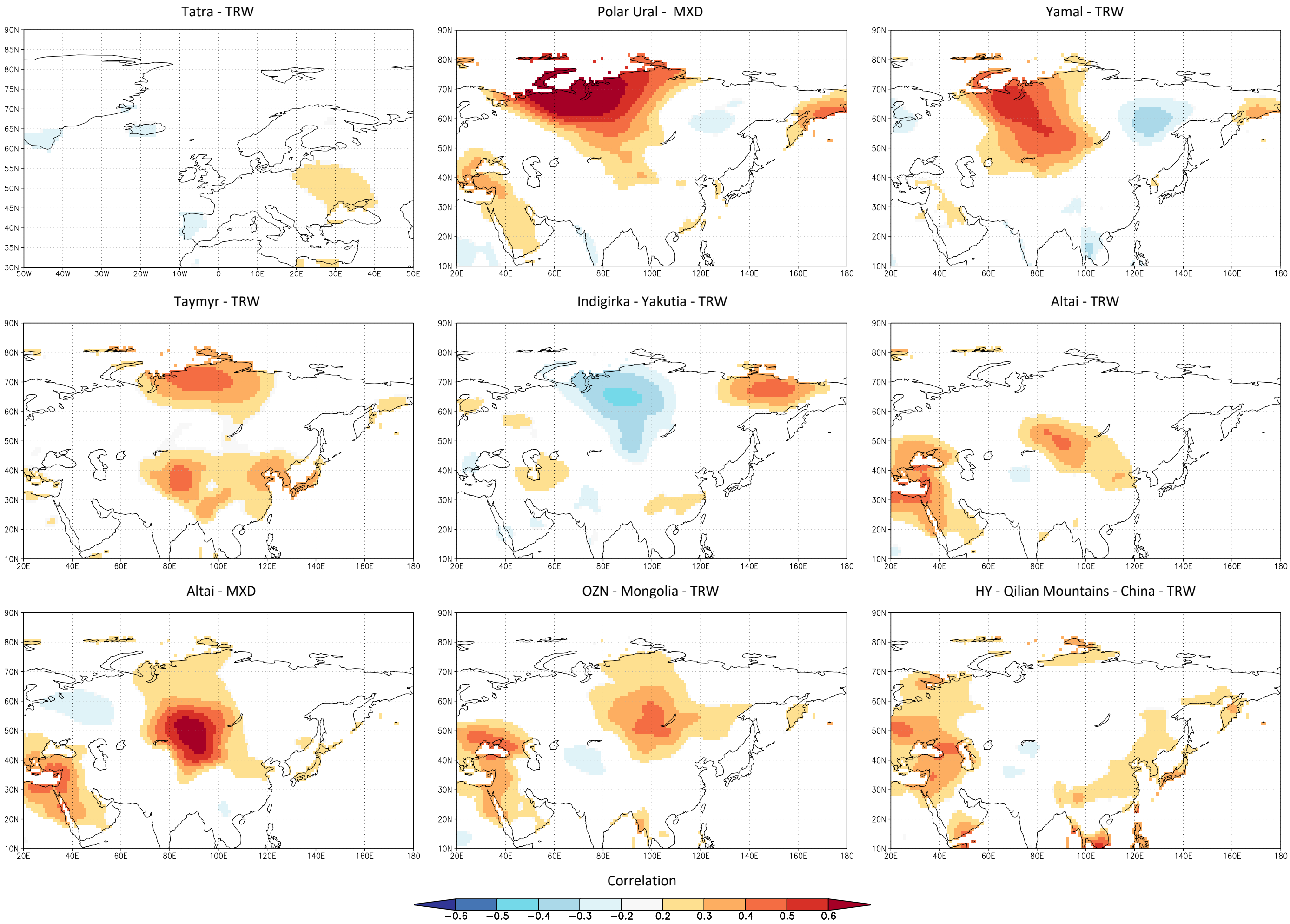

Tatra - TRW
Polar Ural - MXD
Yamal - TRW
Taymyr - TRW
Indigirka - Yakutia - TRW
Altai - TRW
Altai - MXD
OZN - Mongolia - TRW
HY - Qilian Mountains - China - TRW
Correlation
−0.6 −0.5 −0.4 −0.3 −0.2 0.2 0.3 0.4 0.5 0.6

Figure S3. Maps of r^2, R^2, RE and CE obtained for the spatial reconstruction.

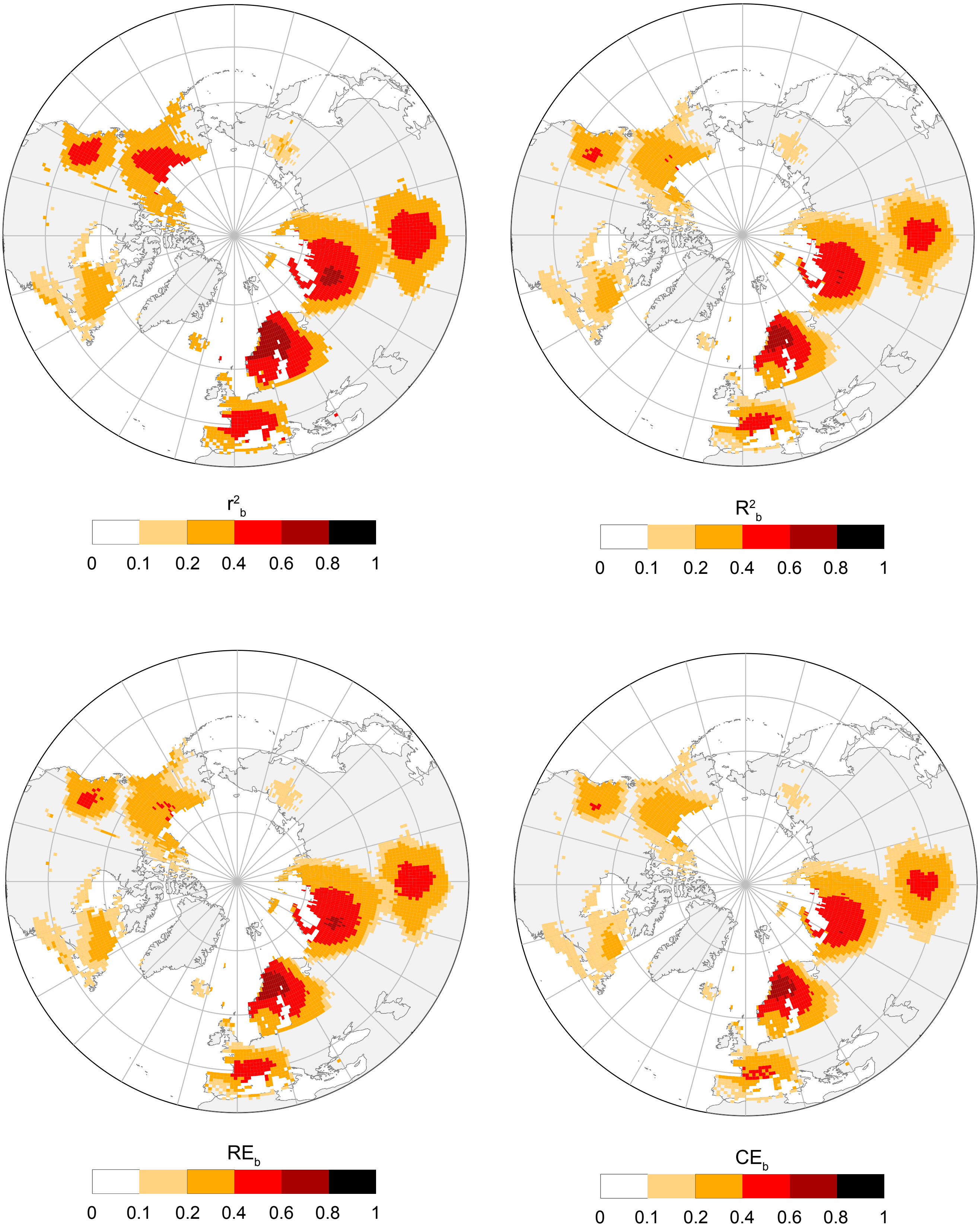
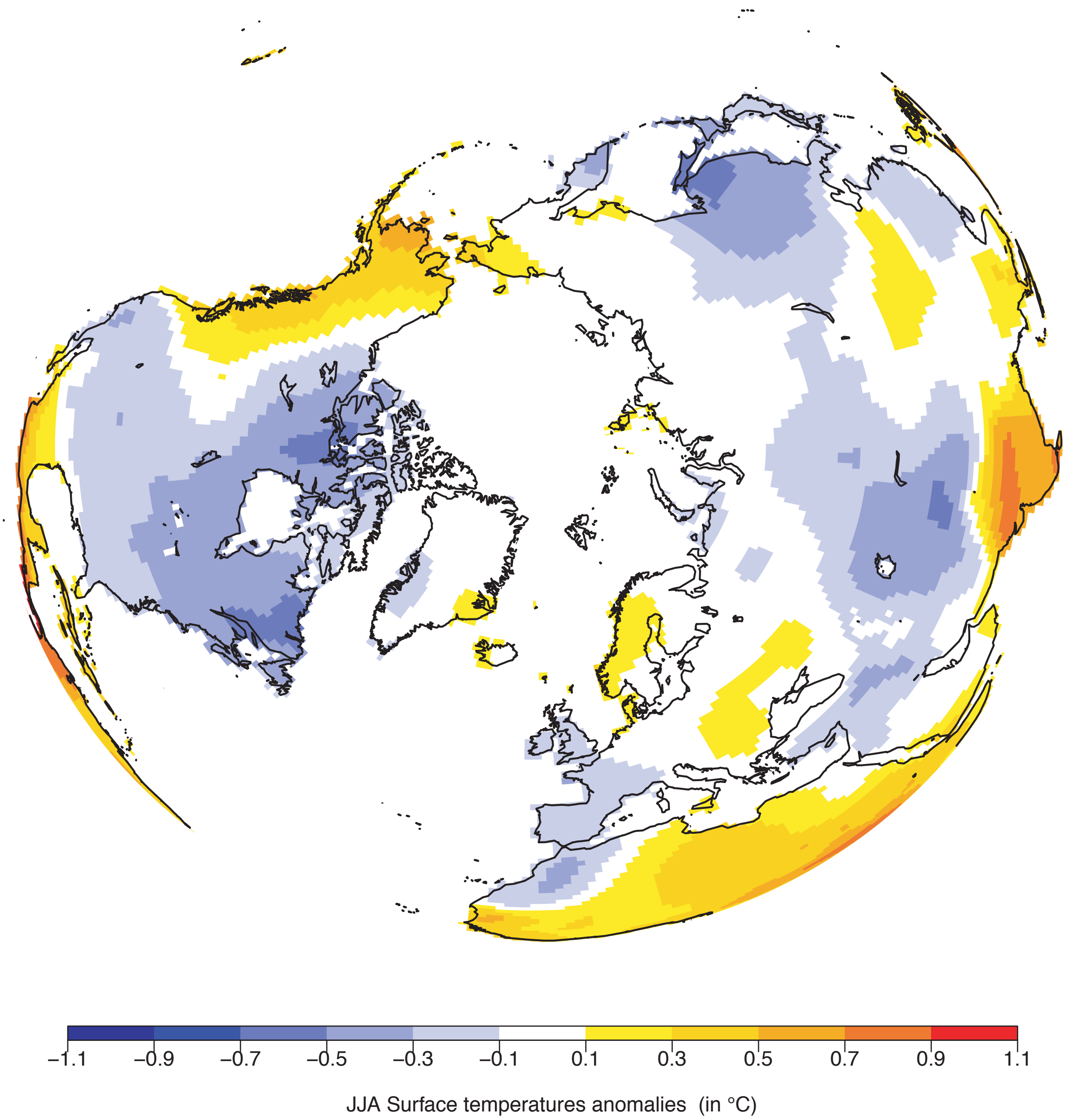


Table S4. Frost rings and light-rings observed in the tree-ring chronologies of the Northern Hemisphere in 1258 and 1259.

Site	Polar Ural	Yamal	Taimyr	Altai	Indigirka	Mongolia Solongotyn Davaa	Subarctic Quebec	Western USA
Time span	*AD 742-1999*	*AD 742-1999*	*BC 431- AD 2006*	AD 462-2007	*BC 359-AD 1998*	*AD 536, 934, 1258, 1259*	*AD 706-1676* *AD 1398-1982*	*BC 3000 - AD 2002*
Species	*Juniperus Sibirica* *Larix sibirica Ledeb*	*Larix sibirica* Ledeb	*Larix gmelinii* Rupr.	*Larix sibirica* Ledeb.	*Larix cajanderi* Mayr.	*Pinus sibirica* Du Tour	*Picea mariana* Mill. BSP	*Pinus Longaeva* *Pinus Aristata*
Reference	*Hantemirov et al. (2004)*	*Hantemirov et al. (2004)*	*Naurzbaev et al. (2002); Sidorova (2003)*	*Myglan et al. (2012); Churakova (Sidorova) et al. (in prep.)*	*Sidorova and Nauzbaerv, 2002; Sidorova 2003; Hughes et al., (in prep.)*	*D'Arrigo et al. (2003)*	*Arseneault and Payette (1998) Fillon et al. (1986)*	*Salzer and Hughes (2007)*
1258	*Frost rings*	*Frost rings*	-	*Frost rings*	-	*Frost rings (latewood)*	*Light rings*	-
1259	*Frost rings*	*Frost rings*	-	*Frost rings*	-	*Frost rings (earlywood)*	-	*Frost rings*
1453	*Frost rings*	*Frost rings*	-	-	-		*Light rings*	*Frost rings*
1601	*Frost rings*	*Frost rings*	-	-	-		*Light rings*	*Frost rings*
1816	-	-	-	-	-		*Light rings*	-

Figure S4. Composite map showing JJA Surface temperatures anomalies following El Nino Events for the period 1950–2014



Text S6 - Evidence for a hot and dry summer in 1259 in Western Europe

In Western Europe, it appears that the climatic impacts of the 1257 Samalas eruption were rather limited in 1259. Most contemporary chroniclers from Germany, Austria, Bohemia, France but also England seem to agree on the fact that weather conditions improved that year. According to mediaeval archives, the summer and autumn were quite hot and dry, harvests were generally more abundant than in 1258 which helped to lower the price of corns and wine in several regions of Europe. These accounts are quite in good agreement with tree-rings records from the Alps and Pyrenees which also suggest the occurrence of warmer conditions in Western Europe in 1259. Here we provide the original Latin text of these historical accounts and their English translations:

Speyer (Germany):

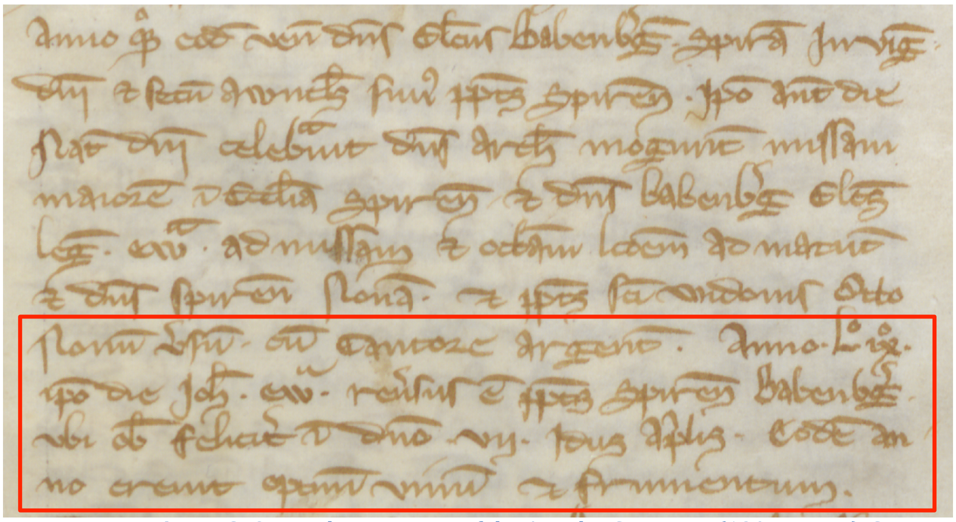


Figure 8. Original manuscript of the Annales Spirenses (13th century). Speyrer Kopialbuch. Generallandesarchiv *Karlsruhe* GLA 67 Nr. 448 fol. 39v.

1259 :

Eodem anno crevit optimum vinum et frumentum.

Annales Spirenses, PERTZ G.H., 1861. Monumenta Germaniae Historica, Scriptores 17, Hanover, pp. 80-85.

Translation: *This year grew an excellent wine and the wheat harvest was optimal.*

Worms (Germany):

Anno 1259 in die apostolorum Petri et Pauli quo fuit estas calida et sicca sic ut a Martio usque ad augustum parum vel nichil pluerit, et tamen vini et omnium frugum fuit abundantia ut vasa carius quam vinum venderentur [...].

Translation: *In the year 1259, on the day of the Apostles Peter and Paul [June 29], the summer was hot and dry. From March to August, little or even no rain fell, however wine and all other fruits of the earth were abundant, so that wine was sold cheaper than the jar (in which it was contained) [...].*

Annales Wormatienses, PERTZ G.H., 1861. Monumenta Germaniae Historica, Scriptores 17, Hanover, pp. 34-73.

1259 :

Coutances (France):

Anno isto scilicet M CC L VIII, in aestate non fuit aestus. Tempus messium et vindemiarum fuit valde pluviosum et frigidum, nec blada bonae collectionis nec vina; nec unquam retroactis temporibus tam debilia vina fuerunt, utpote non matura, viridia, turbida, male sana. Anno sequenti, mense Aprili, fuit mortalitas maxima Parisius, et moriebantur homines quasi subito. Et eodem, scilicet L nono, fecit aestum, fuit tempestuosum in multi locis, fulgura, choruscationes, grando creberrima, et in multi locis mala multa fecit.

Notae Constantienses, DE WAILLY N., DELISLE L., JOURDAIN C.M.G., (eds.), 1894. Recueil des historiens des Gaules et de la France, Vol. 23, H. WELTER Editeur, Paris, pp. 543-546.

Translation : *In this year of 1258, there was no summer during summer. The weather was very rainy and cold at harvest time, neither the crop harvest nor the grape harvest were good. Never before was such a poor wine seen for grapes could not reach maturity; they were green, altered and in poor health. The next year, in April, there was a high mortality in Paris, and the people died almost instantly. This same year, in 1259, there was a heat wave, there were storms in numerous places, lightning, hail, and this repeatedly, causing heavy damage in numerous places.*

Senones (France):

Sed sequens annus (1259) tam temperatus et fertilis extitit, ut adeo bonis habundaret, ut iam nemo preteriti anni inordinationis non reminisceretur.

Richeri Gesta Senoniensis Ecclesiae, WAITZ G. (ed.), 1880. Monumenta Germaniae Historica, Scriptores 25, Hanover, pp. 249-345.

Translation: *The next year (1259) was so temperate and well-disposed that by its fertility it contented mankind so much that they could forget about the infertility of the previous years.*

Strasbourg (France):

Sequenti autem anno (1259) crevit optimum vinum. [...] Anno Domini MCCLIX. Dabatur quartale vini pro IIII sol. et quartale frumenti pro IIII sol. in curia domini de Dalmazingen.

Annales Marbacenses qui dicuntur – Annales Argentinenses Fratrum Praedicatorum, BLOCH H. (ed.), 1907. Scriptores Rerum Germanicarum, Vol. 9, Hanover and Leipzig, pp. 124-133.

Translation: *But the next year grew an excellent wine. [...] Year of the Lord 1259. A quartal of wine was sold for 4 shillings and the quartal of wheat for 4 shillings at the court of the Lord of Dellmensingen*[10]*.*

[10] *Village located in Germany, near Erbach an der Donau in the state of Bade-Wurtemberg.*

England (Saint Alban abbey):

Transiit autem annus ille parum frugifer, sed parcius fructifer, et ut apparuit in quampluribus anno praecedenti dispar et contrarius ; Anglia etenim, quae diu languida diversis diversorum quasi regum potestatibus subjacebat et injuriis, hoc coepit in anno nova succrescente justicia optatis respirare remediis, item cum tota tunc fuerit aestas et maxime in autumpno pluviosa, ita quod circa festum sancti Martini remaneret messis in agris colligenda. Hoc fuit in anno, et maxime in autumpnali tempore, tanta aeris temporis et siccitas, ut fruges, licet tenuissimae, pro voto tamen colligerentur in tempore. Item cum tanta tunc fuisset messis ut si tota salvaretur, duobus fere annis sufficeret, sed sic tota fuit corrupta, ut infra annum multis exinde periclitantibus, deficeret annona. In hoc quidem anno tanta succrevit in modico abundantia, ut ob messis et temporis siccitatem praestaret ex insperato sufficientiam. Fuit insuper annus ille, sicut Anglis parcior in frugibus, ita et Francis in vineis corruptus a potibus.

Flores Historiarum (1067-1264), LUARD H.R. (ed.), 1890. Rerum Britannicarum Medii Aevi Scriptores, Vol. 2, Eyre and Spottiswoode, London, 542p.

Translation: *So that year passed, not very fertile in corn, and very sparing as to its supply in fruit, and, as has often been seen, very unlike and contrary to preceding year. England, however, which had been long languid, lying exposed, as it were to the authority and injuries of different kings, in this year began to enjoy some sort of respite, as justice derived vigour from the application of new remedies[11]. During this year (1259), and especially in the autumn season, there was such fine weather and dry time, that though the crops were thin, they were nevertheless got in in good time, to the farmer's wish. And while a little before (1258), the crop had been so great that if it had been all saved, there would have been enough for two years, and yet it was all so utterly spoilt, that within the year there was actual scarcity, and many were in danger for that reason[12]; now in this year (1259) though the crop was but moderate, there nevertheless was such abundance, that owing to the dry season of the harvest, there was a very sufficient provision made quite unexpectedly. Moreover while this year was in England one of scanty crops, in France the vineyards were utterly spoilt by the rain[13]. As to other matters, it was to the English in many respects a desirable year and to the French one of peace and harmony.*

The Flowers of History (1066-1307), YONGE C.D. (transl.), 1853. Volume 2, Henry G. Bohn, York Street Coven Garden, London, 623 p.

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[11] *This sentence is not complete, the following text is missing: item cum tota tunc fuerit aestas et maxime in autumpno pluviosa, ita quod circa festum sancti Martini remaneret messis in agris colligenda. It should be noted that the translation of historian Charles Duke Yonge (1812-1891) does not in all places correspond to Henry Richards Luard's (1825-1891) edition of the Flower of History. Indeed Yonge's translation and Luard's edition are based on two different manuscripts. Yonge's translation (1853) precedes Luard's edition (1890) and is based on the text originally edited in the 16th century by the Archbishop of Canterbury, Matthew Parker. Luard's edition is based on the more complete Chetham manuscript* (MS. *6712) of which Matthew Parker was not aware when he edited for the first time the Flowers of History (Gransden, 1996). What is the meaning of the omitted Latin sentence? The chronicler states that: the weather was so wet in summer and even more in autumn that around Saint Martin's day (11 November) crops were still found in the fields awaiting collection. This sentence likely refers to the year 1258, since a similar sentence can be found earlier in the section of the Flores Historarium dedicated to the year 1258 (Yonge, 1853, page 357).*

[12] *This sentence also probably refers to the year 1258 as an almost identical sentence referring to the year 1258 can be found in the Chronica Majora written by Matthew Paris (Luard, 1880, page 711).*

[13] *We invite the reader to interpret this section of the text with caution. Available historical sources from France, do not indicate very wet conditions during the summer of 1259 (see texts above). On the contrary they tend to suggest quite dry weather conditions in summer. However, the Norman notes of Coutances (Normandy) suggest that repetitive thunderstorms caused by warm weather and hail did some damage in several locations during the summer of 1259. Although the chronicle doesn't give any description about the nature of damages, we may reasonably assume that the convective storms and hail may have damaged some vineyards.*

Lambach (Austria):

Estas calida et sicca.

Annales Austriae – Continuatio Lambacencis, WATTENBACH W. (ed.), 1851. Monumenta Germaniae Historica, Scriptores 9, pp. 556-561.

Translation: *Hot and dry summer*.

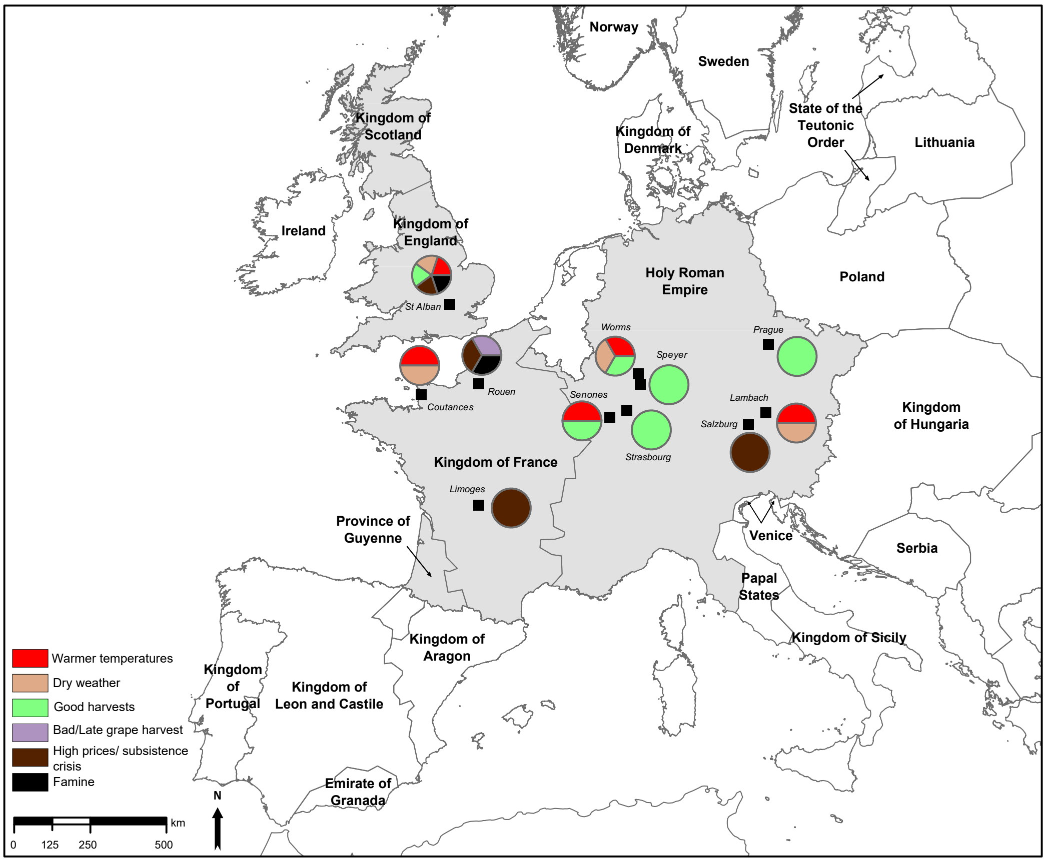
Prague (Czech Republic):

Vinum miri valoris provenit in tota Bohemia.

Cosmae chronica Boemorum – Annalium Pragensium pars I, KOEPKE R. (ed.), 1851. Monumenta Germaniae Historica, Scriptores 9, Hanover, pp. 169-181.

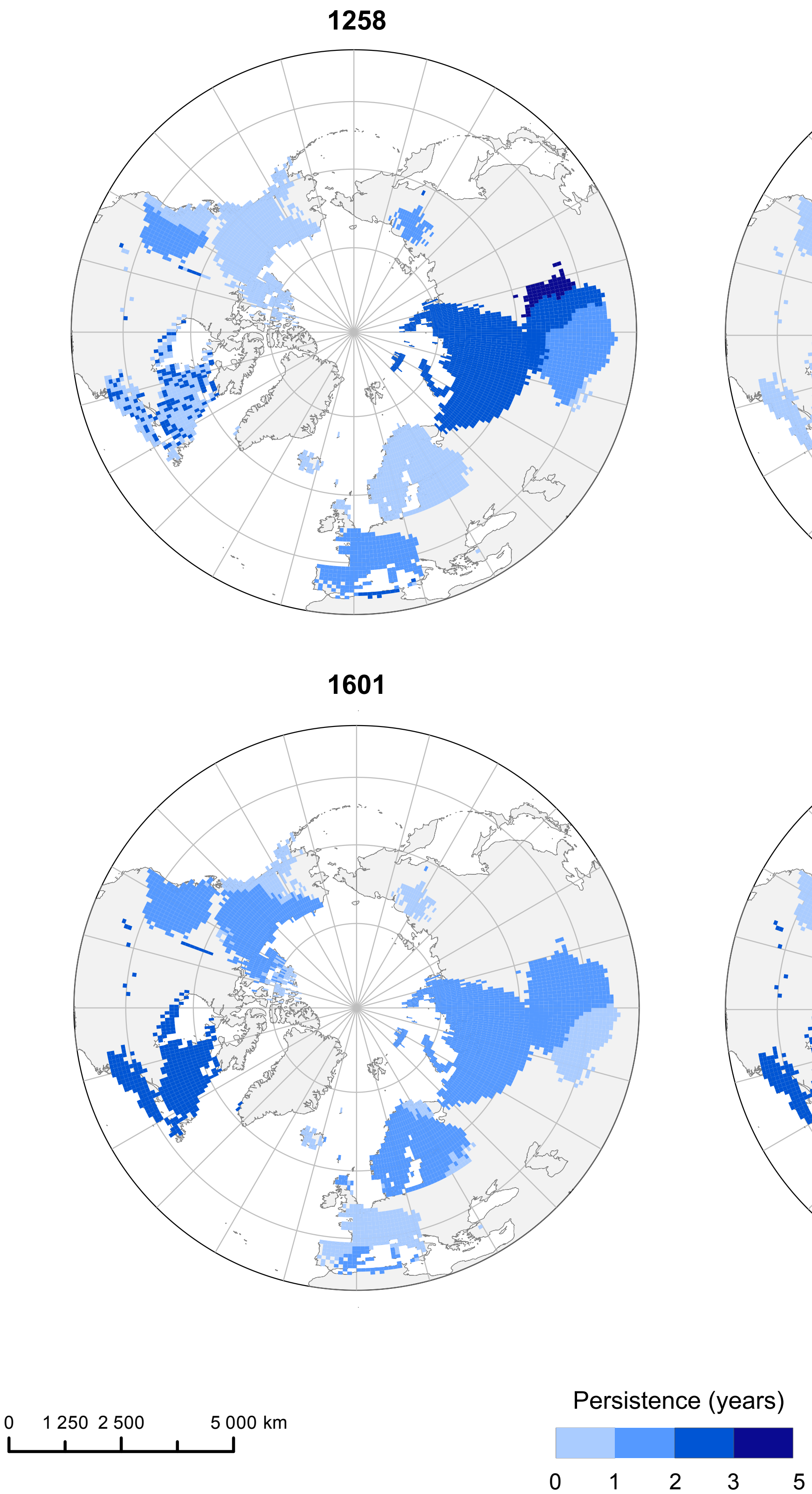
Translation: *A prodigiously fine wine was produced in all Bohemia*

Text S6. Evidence for a hot and dry summer in Western Europe in 1259.

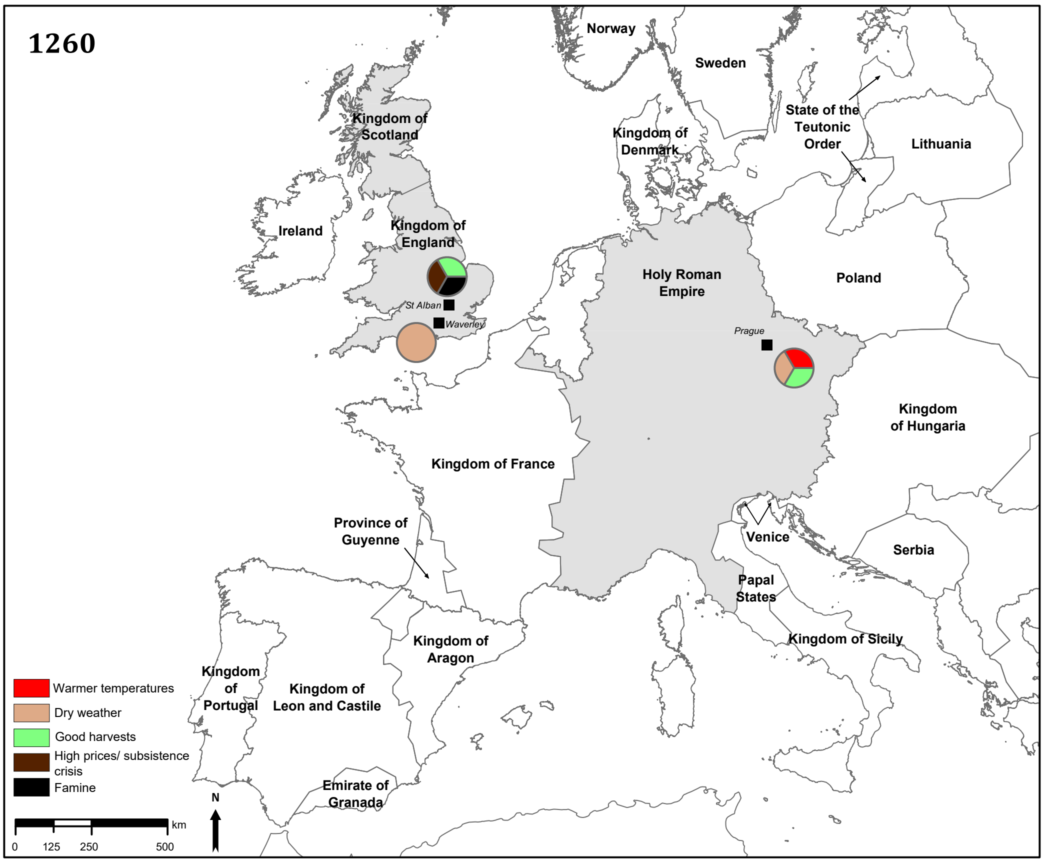


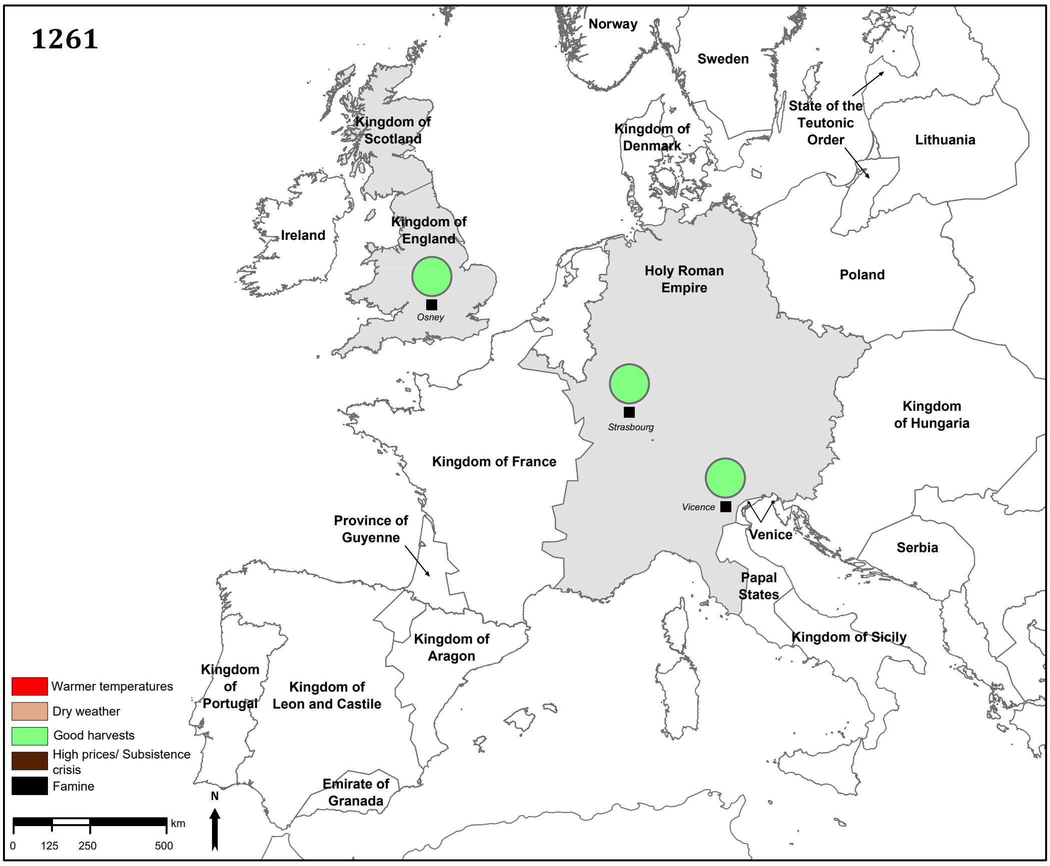
The climate historian Pierre Alexandre has suggested that the bad grape harvests, high prices as well as the famine reported in Rouen (annals of Saint-Catherine-du-Mont in Rouen) in 1259 might in fact have happened in 1258 (Alexandre, 1987; see also Table S1).

Figure S5. Persistence of climatic anomalies after major eruptions.



Text S7. Climatic anomalies in 1260 and 1261 in Europe according to historical archives.





Comment on figure S7 (1260).

The number of narrative sources providing information about the weather conditions of the year 1260 dropped significantly compared to the years 1258 and 1259.

The annals of Prague report the occurrence of a quite warm and hot summer leading to a good production of crops.

In England the situation was more complex and contrasted. According to the Annals of Waverley, the harvest of 1260 was not exceptional following a quite dry summer which ended with cold and wet weather in October and November. The chronicler of Saint Alban also confirms that the crop harvest was not extremely abundant but reports however an excellent harvest of fruits:

"So that year passed by, not very rich in crops, but one which produced great abundance of fruit. For the orchards, and gardens, and woods were all so fertile in their different kinds, that they appeared sufficient to make up for the scantiness of the corn crops, which was very grateful to the eye" (Yonge, 1853, page 389.)

Although harvests were generally more abundant in 1259 and 1260 than in 1257 and 1258, English annals and chronicles suggest that several regions of England were still suffering from high prices and famine in 1260.

Comment on figure S7 (1261).

As in 1260, the number of sources providing information about the weather conditions observed in 1261 are rather limited. But all the sources we could recover report good harvests, especially in England, where the chronicler of Osney noted that in 1261 the fruits of the earth returned after several years of high mortality from hunger.

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