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# A millennium-long ‘Blue Ring’ chronology from the Spanish Pyrenees reveals severe ephemeral summer cooling after volcanic eruptions

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## Abstract

‘Blue Rings’ (BRs) are distinct wood anatomical anomalies recently discovered in several tree species from different sites. While it is evident that they are associated with a cooling-induced lack of cell wall lignification, BRs have yet to be evaluated systematically in paleoclimate studies. Here, we present a continuous wood anatomical assessment of 31 living and relict pine samples from a high-elevation site in the central Spanish Pyrenees that span the period 1150–2017 CE at annual resolution. While most BR years coincide with cold summer temperatures and many BRs follow large volcanic eruptions, some were formed during overall warm summers. We also see a differential response between eruptions: the Samalas eruption is followed by 80% BRs in 1258, but only a modest signal is evident after the 1815 Tambora eruption, and there are no wood anatomical effects of the Laki eruption in 1783–1784. Apparently linked to a cluster of tropical eruptions in 1695 and 1696 CE, 85% BRs occurred in 1698. This new wood anatomical evidence is corroborated by the record of sulphur deposition in polar ice cores, and corresponds with catastrophic famine and unprecedented mortality in Scotland. The extremely rare occurrence of consecutive BRs in 1345 and 1346 marks the onset and spread of the Black Death, Europe’s most devastating plague pandemic. In their ability to capture severe ephemeral cold spells, as short as several days or weeks, BR chronologies can help to investigate and understand the impacts of volcanism on climate and society.

## 1. Introduction

The summer cooling signatures of large volcanic eruptions have been intensively studied. Numerous factors influence the climate response to volcanism including eruption intensity and sulphur emission, source location, seasonal timing and climate sensitivity (Robock 2000, Oppenheimer 2011, Timmermann 2012, Esper *et al* 2013, Toohey *et al* 2019). Aside from recent eruptions, such as Pinatubo in 1991 (McCormick 1992, Russell *et al* 1996), for which

abundant direct observations are available, proxy data are needed to date and reconstruct the direct and indirect climatic effects of past volcanism (Gao *et al* 2008). Records of accumulated ice in Greenland and Antarctica represent the most reliable and longest archives of global volcanic sulphur emissions (Zielinski *et al* 1994, 1996, Zielinski 1995).

The available glacio-chemical records are, however, associated with variable and uneven dating uncertainties (Sigl *et al* 2015, Svensson *et al* 2020). Since volcanic sulphur excesses in ice cores are

widely used to derive the radiative forcing magnitude and timing in climate model simulations (Crowley 2000, Otto-Bliesner *et al* 2016), the precise dating of past eruptions is essential (Oppenheimer *et al* 2017, Büntgen *et al* 2017a), though often controversial (Dull *et al* 2019, Smith *et al* 2020). Even small dating errors will have significant effects on proxy-model comparisons (Anchukaitis *et al* 2012, Büntgen *et al* 2014, 2018, Esper *et al* 2015), and on investigations into the relationships between volcanism, climate and society (Sigl *et al* 2015, Büntgen *et al* 2016, 2020, Di Cosmo *et al* 2017, Oppenheimer *et al* 2018, Guillet *et al* 2020).

Tree ring-based reconstructions of regional to hemispheric summer temperature variability have been used to detect and quantify the climatic fingerprints of some of the largest volcanic eruptions during past centuries (Briffa *et al* 1998, Krakauer and Randerson 2003, Schneider *et al* 2015, Stoffel *et al* 2015, Wilson *et al* 2016, Anchukaitis *et al* 2017, Guillet *et al* 2017, Büntgen *et al* 2020). Maximum latewood density (MXD) is considered a more precise proxy for summer temperatures compared to tree-ring width (TRW) (Büntgen *et al* 2006, Schneider *et al* 2015, Stoffel *et al* 2015, Björklund *et al* 2019), which is subject to the effects of biological memory (Frank *et al* 2007, D'Arrigo *et al* 2013, Esper *et al* 2015). However, both parameters reflect an integrated response over most of the growing season (Fritts 1976, Briffa *et al* 2002, Büntgen *et al* 2011, Cuny *et al* 2014), and therefore do not express severe ephemeral cooling events lasting days or a few weeks only (see figure 4 and associated discussion in Büntgen *et al* 2017b for a better understanding of the biotic and abiotic factors of wood formation in *Pinus uncinata* at high-elevation sites in the central Spanish Pyrenees).

In addition to so-called 'Frost Rings' (FRs; collapsed and deformed early or latewood cells and rays) and 'Light Rings' (LRs; none or only a few layers of latewood cells), which can result from ephemeral cooling events during the growing season (Lamarche and Hirschboeck 1984, Filion *et al* 1986, Tardif *et al* 2020), 'Blue Rings' (BRs) are a newly discovered indicator of the degree of cell wall lignification that becomes visible in double-stained anatomical thin-sections (Piermattei *et al* 2015, Crivellaro *et al* 2018, Tardif *et al* 2020). Since cell wall lignification in wood seems to be thermally controlled (Gindl *et al* 2000, Körner *et al* 2019, Crivellaro and Büntgen 2020), we expect continuous BR assessments to provide additional insights into the climatic effects of past volcanism.

Here, we use wood anatomical and biochemical measurements of 31 annually-resolved and absolutely-dated pine TRW series from the upper treeline in the Spanish central Pyrenees to reconstruct the occurrence of BRs over the past 850 years. Through a comparison with different state-of-the-art wood anatomical, biochemical and spectroscopic

techniques (figure 1), we aim to explore the physiological and mechanistic processes relevant to the formation of BRs.

## 2. Materials and methods

Increment cores from 20 living trees and disc samples from 198 relict logs and snags of Mountain pines (*Pinus uncinata* Mill.) were collected at the upper treeline in the Spanish central Pyrenees. All trees in this remote northern limit of the Aiguestortes I Estany de Sant Maurici National Park grew above 2000 m asl ( $\sim 42^{\circ}40'N$  and  $00^{\circ}50'E$ ). The TRWs of all samples were measured, cross-dated, and validated against existing, millennium-long TRW and MXD chronologies from the same region (Büntgen *et al* 2008, 2017b). In all samples, the occurrence of LR and FR was recorded, and a selection of 31 samples, evenly distributed across the past millennium, was made for the investigation of BRs. Wood anatomical thin-sections of 15  $\mu m$  thickness were prepared (Gärtner and Schweingruber 2013, Gärtner *et al* 2015), and each sample was bleached with sodium/potassium hypochlorite to decolour cell walls and to remove undesired cell content. All microsections were stained with a blend of Safranin (red) and Astra Blue (blue) to visualise lignified and less lignified cell walls in red and blue, respectively. In this study, Astra Blue refers to a mixture of 0.5 g Astra Blue powder dissolved in 100 ml distilled water and 2 ml acetic acid, whereas Safranin refers to a mixture of 0.1 g Safranin powder dissolved in 100 ml distilled water. In our laboratory, we mix Astra Blue and Safranin at the proportion of 4:1 (i.e. four-times Astra Blue and one-time Safranin).

The stained microsections were first washed with water and then with ethanol at increasing concentrations (Gärtner *et al* 2015), and finally embedded under a cover glass with a permanent hardener. In this study, we define a complete BR as a tree ring in which we are able to visually detect a distinct layer of completely blue cell walls (figure 1(C)), whereas a partial BR (pBR) is characterized by a non-continuous layer of blue cell walls and/or by only blue inner layers of cell walls. It is evident that the lack of cell wall lignification is always stronger in BRs compared to pBRs. However, in both cases, we can assume that the bluer the cell walls, the less lignified they are (Gerlach 1984, Piermattei *et al* 2015, Ghislan *et al* 2019, Crivellaro and Büntgen 2020, Tardif *et al* 2020).

In order to compare our new BR record against pine growth and summer temperature, we used the existing TRW and MXD chronologies, as well as the mean May–June and August–September temperature reconstruction from the same site (Büntgen *et al* 2017b). As a proxy for volcanic forcing of large-scale climate variability, we use the annual sums obtained from monthly-resolved estimates of stratospheric aerosol optical depth (SAOD) over the

Northern Hemisphere (NH) extra-tropics ( $>30^{\circ}\text{N}$ ), derived from polar ice core records (Toohey and Sigl 2017). Superposed epoch analysis (SEA; see Rao *et al* 2017 for methodological details) was used to quantify regional to hemispheric warm-season temperature variation and volcanic forcing for those years in which (i) at least 20% of the observations for that year contain BRs ( $n = 38$ ), (ii) at least 20% pBR ( $n = 47$ ), and (iii) all years in which either 20% BRs or pBRs occurred ( $n = 71$ ).

Owing to their exceptionally good preservation and continuous timespan from 1320–1850 CE (figure S1 (available online at <https://stacks.iop.org/ERL/15/124016/mmedia>)), three relict pine samples were selected for an additional inspection of intra- and inter-annual changes in wood polymer composition (see supplementary materials for details), as well as to probe further the physiological and mechanical drivers of different cell anatomical properties. Lumen area and cell wall thickness were measured in BR years, as well as in the three years before and after each BR using the image analysis software ROXAS (von Arx and Carrer 2014). Intra- and inter-annual wood density profiles values for the same sequences were obtained from the Walesch 2003 x-ray densitometer (Schweingruber *et al* 1978, Eschbach *et al* 1995), as well as from digital scans processed by the CDendro/CooRecorder software (version 9.3.1—Cybis Elektronik and Data; Björklund *et al* 2019).

Since neither the anatomical nor the image-based wood density surrogates provide quantitative measures of the lignin content in cell walls, we applied Raman spectroscopy. First,  $\sim 0.5$  mm thick blocks were measured to acquire low-resolution Raman images across several consecutive rings, followed by high-resolution imaging of the tree rings 1335, 1338 and 1345 on 10–20  $\mu\text{m}$  thin-sections at 0.3  $\mu\text{m}$  lateral resolution to define changes in wood polymer composition (Agarwal 2006, Gierlinger and Schwanninger 2006, Gierlinger *et al* 2012). While removing possible disturbance signals due to cosmic rays and applying a baseline correction, the full Raman spectrum was recorded from 650–1750  $\text{cm}^{-1}$  (see supplementary materials for details). We focussed on spectral bands at  $\sim 1600$ , 1637 and 1652  $\text{cm}^{-1}$  that are representative of changes in lignin, pinosylvins (Belt *et al* 2017, Felhofer *et al* 2018) and resin acids, respectively (see supplementary material for a detailed description of the Raman spectroscopic procedure).

### 3. Results

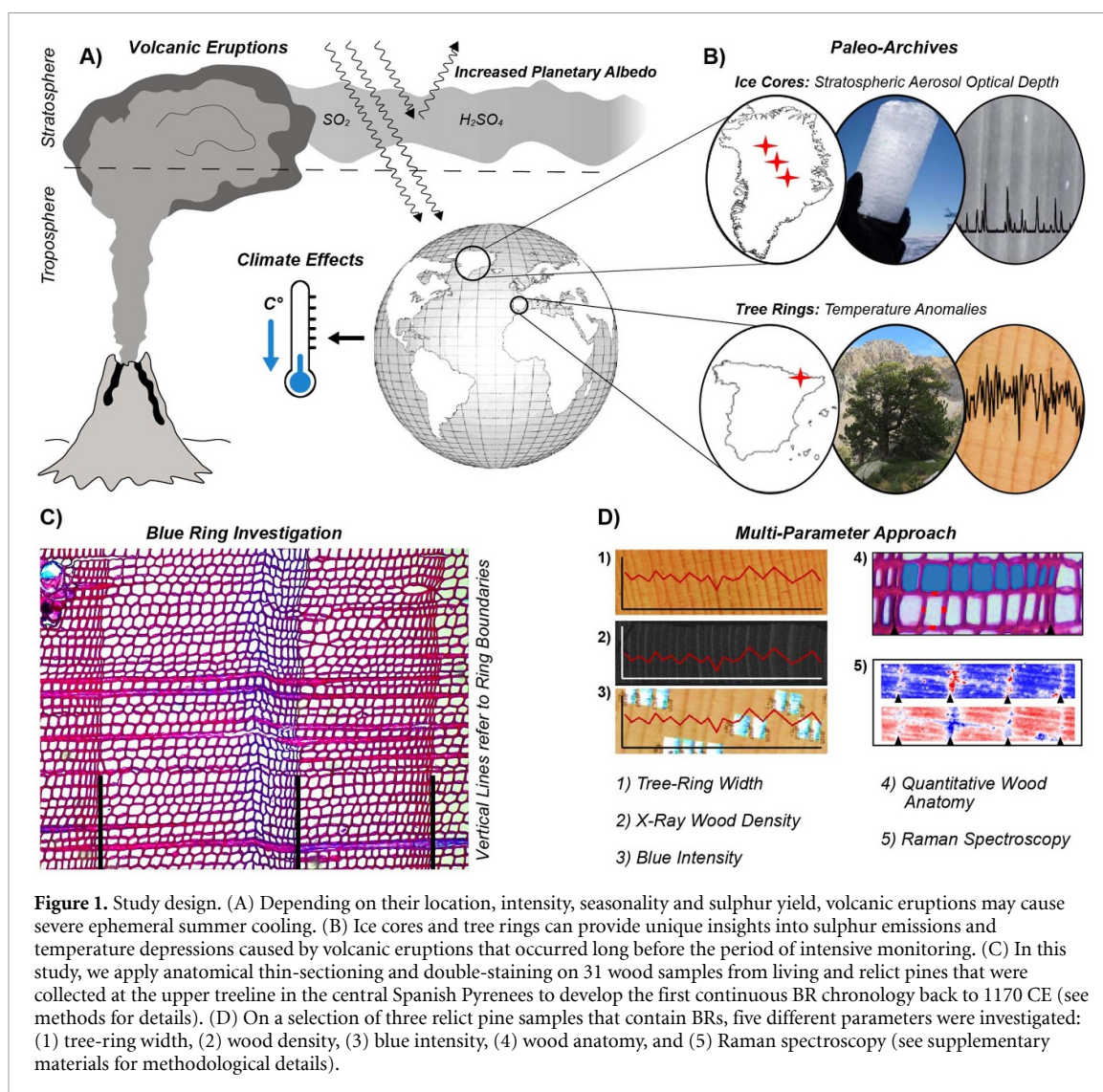
A total of 120 BRs and 177 pBRs were identified in 31 living and relict pine samples between 1170 and 2017 CE (figure 2; table S1). Only three samples were completely devoid of BRs, and another three samples contained only one BR. Sample size ranged from two trees at the record's beginning and end, to 15 trees

in the mid-15th century (figure 2(B)). The occurrence of BRs generally coincides with low MXD and narrow TRW (figure 2(C)). The relative and absolute occurrence of BRs per year ranges from 7%–100% and from 1–11 cases, respectively. The most pronounced anatomical signal during the past 850 years is found in 1698 CE, when 11 out of 13 trees contained BRs (figure 2; table 1). There are 38 and 47 years in which more than 20% of the total number of rings are either BRs or pBRs, respectively (figure 3; table S1). Like BRs and pBRs, the highest frequency of FRs and LR occurs in the middle of the 16th and 17th centuries (figure 3). LRs are most abundant in 1576, 1587, and 1552 CE, and LRs in 1698 and 1714 coincide with BRs. The wood formed in 1714 not only exhibits BRs and LRs but also a high frequency of FRs in the latewood. Latewood FRs are characteristic features in 1587 and 1480, whereas the highest frequency of earlywood FRs occurs in 1523 and 1516 CE (figure 3).

Most of the BRs and pBRs coincide with relatively cold summers (figure 4(B)), often following large volcanic eruptions (figure 4(C); tables 1, S1). Cooling in the mid-13th century, as well as around 1700, and again in the early-19th century, coincides with an increase in the intensity and frequency of BR and pBR years. The longest BR-free periods, 1180–1224 and 1835–1884, coincide with intervals of comparatively low SAOD. The timing of several known equatorial eruptions, including those of Samalas and Kelut (Indonesia), Huaynaputina (Peru), Tambora (Indonesia), Cosigüina (Nicaragua) and Krakatau (Indonesia) in 1257, 1586, 1600, 1815, 1835 and 1883, respectively, coincides with substantial BR and pBR frequencies in the following years 1258, 1587, 1601, 1816, 1835 and 1884/85 CE. However, the cell wall lignification of high-elevation pines in the Pyrenees does not appear to have responded to the prominent high-latitude eruptions of Katla and Laki (both Iceland), or Katmai (Alaska) in 1210, 1783/84 and 1912, respectively. While the vast majority of BRs and pBRs are discrete, consecutive BRs and pBRs only occur in 1345/46, 1674/75 and 1808/1809, timings that also parallel significant, though yet unidentified, eruptions recognised in glacio-chemical records (figure 4(C); tables 1, S1).

Results from the SEA confirm that most of the BRs and pBRs were formed during exceptionally cold summers over the western Mediterranean Basin (figure 5; table S2), which in turn tend to coincide with increased volcanic forcing that triggered longer-term summer cooling at the hemispheric-scale. Significant ( $p < 0.001$ ) and sharp regional May–June and August–September temperature depressions of  $-1.59^{\circ}\text{C}$  ( $\pm 0.66^{\circ}\text{C}$ ),  $-1.39^{\circ}\text{C}$  ( $\pm 0.65^{\circ}\text{C}$ ) and  $-1.30$  ( $\pm 0.69^{\circ}\text{C}$ ) coincide with 38 BR years, the 47 pBR years and the 71 combined instances, respectively. For the same years, SAOD exhibits the



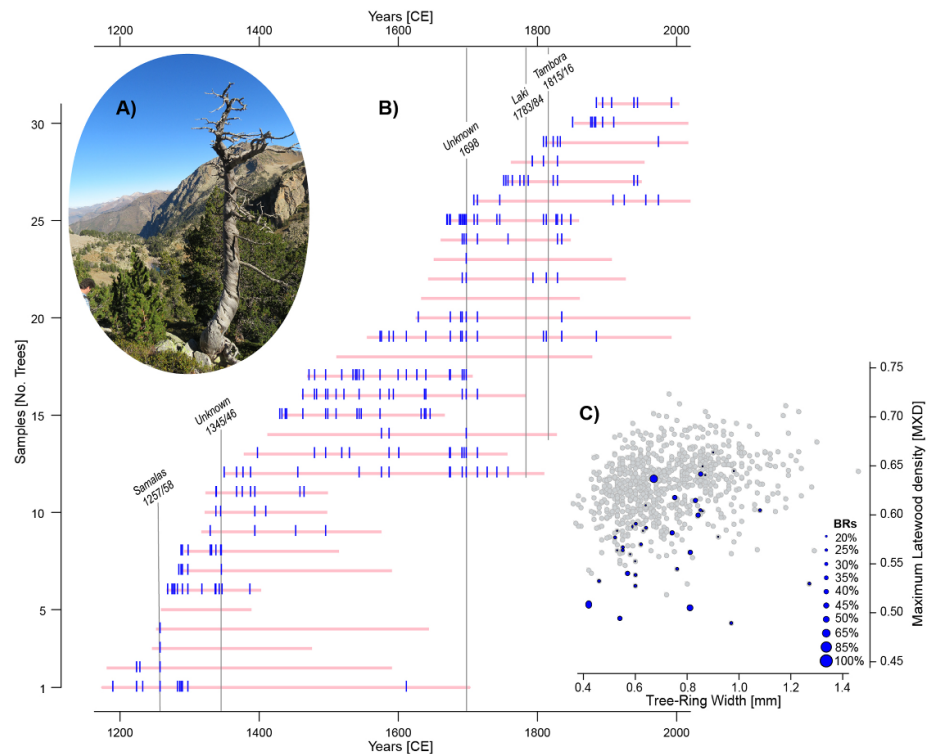


**Table 1.** Blue Ring ranking. The highest occurrence of BRs and pBRs in decreasing order and associated with volcanic eruptions that possibly caused the anatomical features. For each year, the total number of samples (No. Samples), the total number of BR and pBRs, as well as the percentage of BRs and pBRs are shown together with the available information on historical volcanic eruptions that occurred in the same year or the year before BR formation.

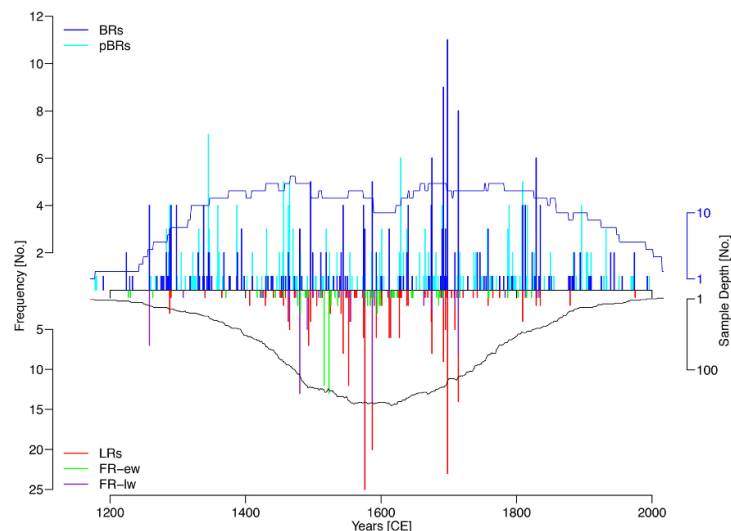
Year	No. Sample	No. BRs	No. pBRs	% BRs	% pBRs	Volcanic Eruption	Eruption Location	Estimated Eruption Date
1698	13	11	0	85	0			
1258	5	4	1	80	20	Samalas	Indonesia	1257
1714	13	8	1	62	8			
1233	2	1	0	50	0			
1298	8	4	0	50	0			
1288	7	3	4	43	57			
1675	14	6	4	43	29			
1587	12	5	1	42	8	Kelut	Indonesia	1586
1835	12	4	4	33	33	Cosigüina	Nicaragua	20 Jan 1835
1809	13	4	5	31	38			
1345	11	2	7	18	64			
1601	10	1	3	10	30	Huaynaputina	Peru	19 Feb 1600
1884	10	1	2	10	20	Krakatau	Indonesia	26 Aug 1883
1816	13	0	4	0	31	Tambora	Indonesia	10 Apr 1815

largest and most significant ( $p < 0.05$ ) increases of 0.29 ( $\pm 0.60$ ), 0.52 ( $\pm 0.60$ ) and 0.38 ( $\pm 0.56$ ). The SEA patterns confirm common knowledge (figure 5):

MXD-based temperature reconstructions capture severe summer cooling and rapid recovery, and the SAOD record reflects the approximate timing



**Figure 2.** Blue Rings in the Spanish Pyrenees. (A) Example of a relict Mountain pine (*Pinus uncinata* Mill.) at the upper treeline in the central Spanish Pyrenees treeline (above 2000 m asl). (B) Horizontal pink lines show the time span of each of the 31 pine samples (see figures 3 and 4 for the number of samples in each year), with the vertical blue lines referring to the occurrence of BRs. Grey vertical lines in the background highlight the most important volcanic eruptions that are discussed in this study. (C) Comparison between the raw maximum latewood density values (MXD;  $\text{g cm}^{-3}$ ) and the raw tree-ring width values (TRW; mm) in 420 series from our sampling location (Büntgen et al 2017b) against the BR years (superimposed as blue dots). The size of the blue dots reflects the percentage of BRs identified in a particular year (20%–100%).

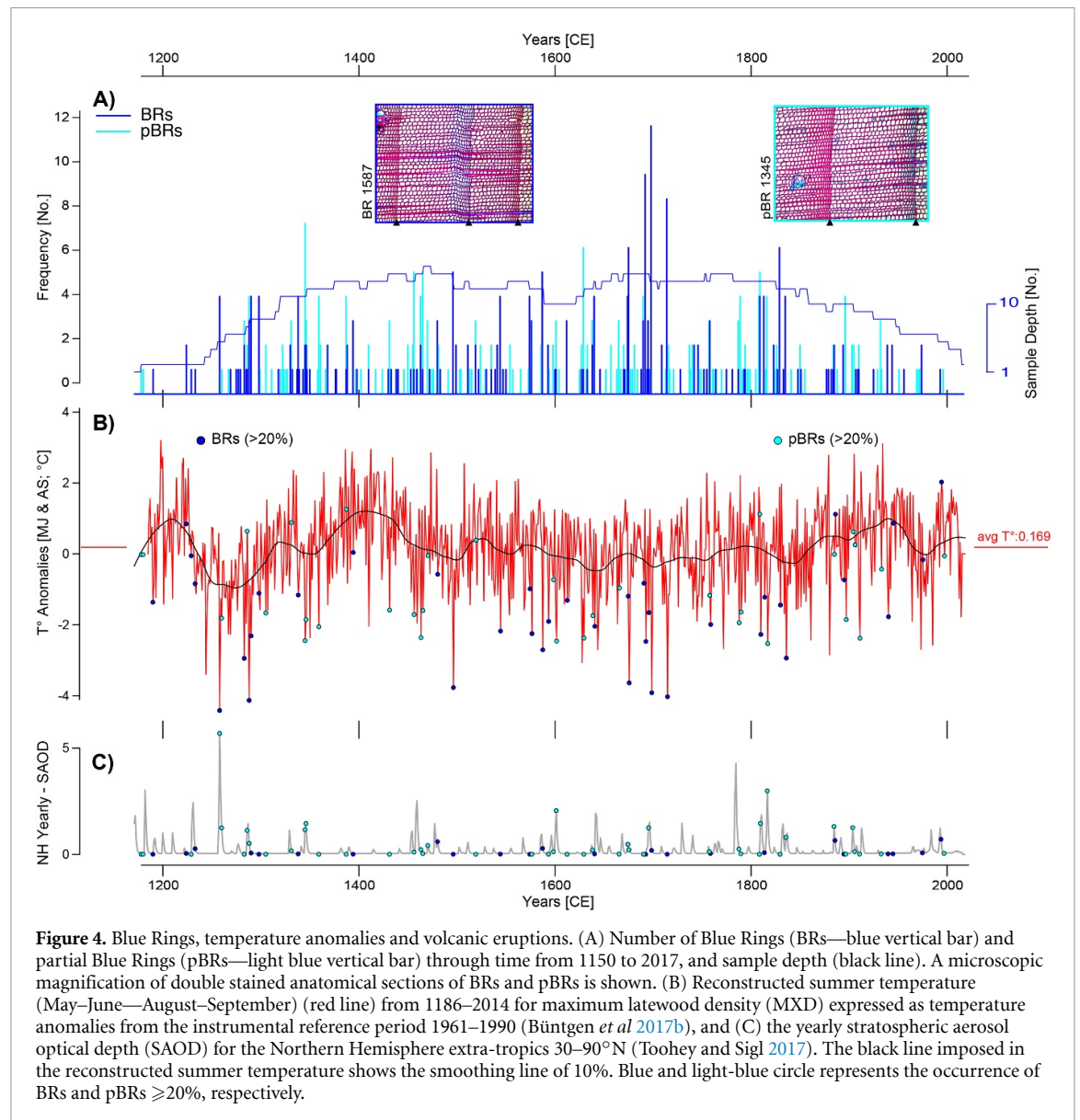


**Figure 3.** Pointer years and Blue Rings. Mirror bar plot of the frequency of BRs (blue) and pBRs (light blue), and other pointer years: light rings (LRs—red), frost rings in earlywood (FRs-ew—green) and in latewood (FRs-lw—violet) from 1170–2017 CE. The frequency expressed as a total number represented in the left y-axes differ from the occurrence of BRs and pBRs (1–12) and the other pointer years (1–25). The sample depth represented in the right y-axes differs from the occurrence of BRs and pBRs (1–31 samples) and the other pointer years (1–198 relict logs or snags discs).

of volcanic forcing but dating uncertainty must be considered.

Agreement between BRs, pBRs and reduced TRW and MXD is confirmed by the continuous intra- and

inter-annual assessment of three relict wood samples (figures S1, S2). Both, the cell lumen area and cell wall thickness in the latewood of BR years in these samples are reduced in comparison to fully lignified rings



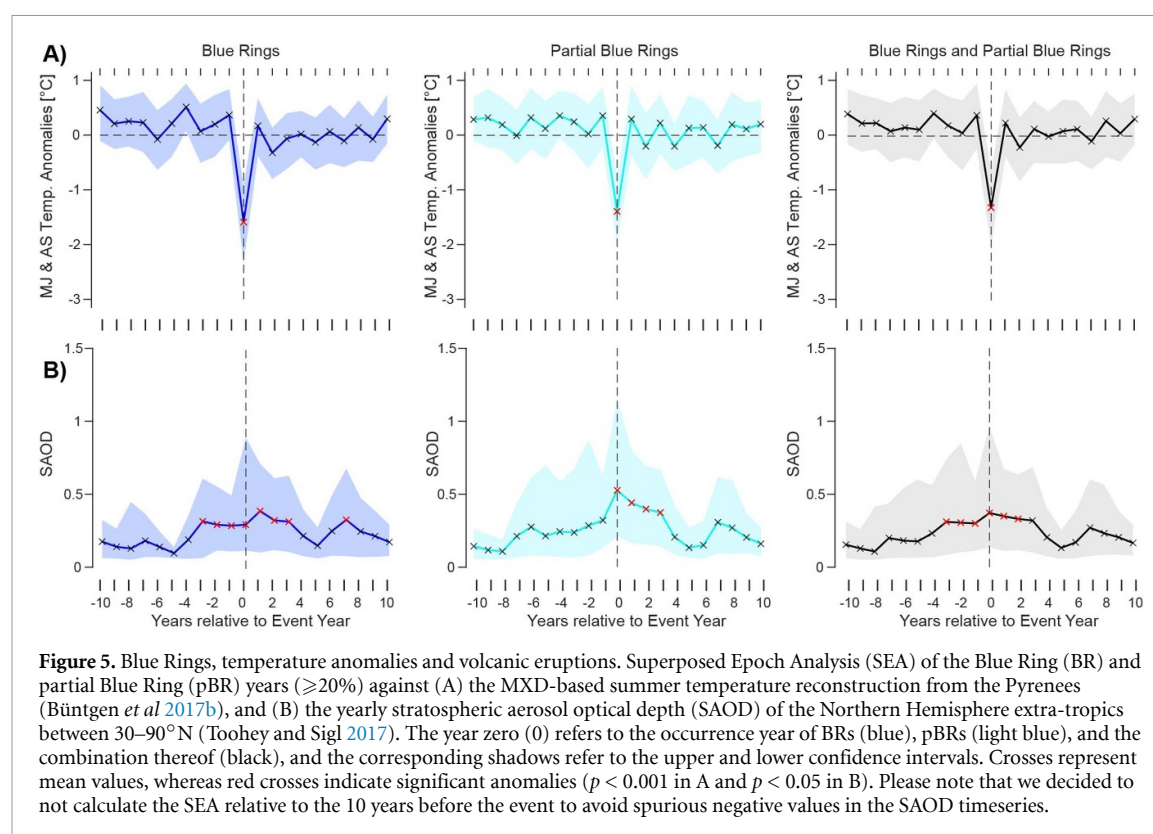
**Figure 4.** Blue Rings, temperature anomalies and volcanic eruptions. (A) Number of Blue Rings (BRs—blue vertical bar) and partial Blue Rings (pBRs—light blue vertical bar) through time from 1150 to 2017, and sample depth (black line). A microscopic magnification of double stained anatomical sections of BRs and pBRs is shown. (B) Reconstructed summer temperature (May–June–August–September) (red line) from 1186–2014 for maximum latewood density (MXD) expressed as temperature anomalies from the instrumental reference period 1961–1990 (Büntgen *et al* 2017b), and (C) the yearly stratospheric aerosol optical depth (SAOD) for the Northern Hemisphere extra-tropics 30–90°N (Toohey and Sigl 2017). The black line imposed in the reconstructed summer temperature shows the smoothing line of 10%. Blue and light-blue circle represents the occurrence of BRs and pBRs  $\geq 20\%$ , respectively.

(figures S3, S4). Interestingly, the latewood of BRs is characterised by thin cell walls (figure S5), whereas the cell wall thickness in fully lignified rings usually increases towards and throughout the latewood. The Raman spectroscopy reveals differences in resin acids and the phenolic combination of pinosylvin and lignin between BRs and fully lignified rings (figure S6). The most distinct Raman signals for pinosylvin (at  $1637\text{ cm}^{-1}$ ) and resin acids (at  $1652\text{ cm}^{-1}$ ) are found in the cell walls and cell corners of the pBRs in 1338 and 1345 CE (figure S7).

#### 4. Discussion and conclusions

This study strongly suggests that BRs and pBRs can be considered as a new indicator of severe ephemeral cold summer temperatures, with BRs formed at lower summer temperatures than pBRs. Moreover, our findings suggest that BR and pBR occurrence is not limited to a few trees nor influenced by tree

age. The highest frequency of BRs, pBR, as well as FRs and LR occurred during the coldest period of the Little Ice Age in the Pyrenees (Büntgen *et al* 2008, 2017b, Morellón *et al* 2011) (figures 3, 4). Moreover, we found significant agreement between BRs and low MXD (figure 2(C)), because cell wall thickening is compromised during cold growing seasons (Filion *et al* 1986, Schweingruber 1993, Vaganov *et al* 2006), and cell wall lignification is limited by temperature (Gindl *et al* 2000, Crivellaro and Büntgen 2020). However, the Walesch-based relative MXD values are not directly associated with the lignin content of the cell walls (Schweingruber *et al* 1978, Büntgen *et al* 2017b). What remains to be explained are those few years where BRs and pBRs are associated with high MXD and positive (reconstructed) temperature departures (figures 2(C), 4(B)). In such instances, we can only speculate on what might be responsible for inhibiting lignin deposition. The first explanation is that short and late-growing season



cold spells affect the occurrence of BRs and pBRs (Piermattei *et al* 2015), but do not have a meaningful negative effect on either MXD or TRW. This could be the result of a week or even a few days of anomalously cold-wet conditions during summer affecting the newly developed cells.

Another potential explanation for the observed positive temperature response may involve the role lignin plays in enhancing the mechanical strength of cell walls, enabling plants to grow tall and transport water to great heights (Niklas 1992, Meents *et al* 2018). Such a line of inquiry will eventually lead back to how environmental conditions trigger auxin production (Mroue *et al* 2018), and what amounts of auxin are required for regulating lignin production, much of which we just do not know for many species and locations. What is abundantly clear is these anomalous warm-season BR observations represent a reliable indicator, manifest by the number of times they are found in different samples in the same year, of a rare condition that in the Pyrenees have occurred less than a dozen times in the past 800 years. Whether the responsible conditions are endogenous or exogenous, including possible drought stress at the upper treeline (Galván *et al* 2015), remains to be explored. A good position from which to start this exploration would be armed with a contiguous BR chronology from temperature sensitive trees at a location where daily, possibly even hourly climate data are available.

Another source of possible uncertainty is related to the fact that the qualitative double-staining

technique with Safranin and Astra Blue, while a reliable indicator (Baldacci-Cresp *et al* 2020) is not a direct measure of cell wall lignification. Our results from Raman spectroscopy are not conclusive either (figures S6, S7). Beside lignin, other aromatic compounds such as pinosylvin, the spectral properties of which partly overlap with those of lignin (Felhofer *et al* 2018), were also detected in the cell walls. However, Raman imaging revealed an increase of phenolic extractives (pinosylvin and resin acids) in the BRs and pBRs of 1338 and 1345 CE. This finding raises the question whether the synthesis of these compounds might be a protective response to climatically-driven stress or aromatic moieties unrelated to lignification. Raman spectroscopy captured and envisaged extractive phenolic content in the lumen, walls and corners of the analysed cells (figure S7), which is consistent with the findings of Belt *et al* (2017) and Felhofer *et al* (2018). Pinosylvin is a plant secondary metabolite belonging to the stilbene family (see the molecular structure in figure S7(D)). This metabolite is an effective fungicide that occurs in pine heartwood (Hovelstad *et al* 2006) and is known to accumulate in cells in response to cold climates (Erdtman and Rennerfelt 1944, Joosen *et al* 2006, Chong *et al* 2009, Felhofer *et al* 2018). Moreover, trees can reduce the consumption of nutrients in response to external stressors, which increases the rate of secondary metabolite production (Rudman 1966, Stewart 1966). The high level of additional phenolic compounds that we measured in BR years might result from an increase of metabolic products due to a decreased



demand for nutrients during cold summer events (Metsämuuronen and Sirén 2019). Despite much progress, we still lack a comprehensive understanding of the processes involved in cell wall lignification and secondary metabolite production in trees (Donaldson 1991, Gindl and Grabner 2000, Ramakrishna and Ravishankar 2011, Crivellaro and Büntgen 2020).

In conclusion, our continuous wood anatomical assessment of 31 living and relict pine samples from a high-elevation, treeline site in the central Spanish Pyrenees (Büntgen *et al* 2008, 2017b) shows that the majority of BR years since 1150 CE coincide with cold summer temperatures. While many BRs follow large volcanic eruptions, such as 80% BRs in 1258 after Samalas (Vidal *et al* 2016, Guillet *et al* 2017), some were formed during overall warm summers as in 1232/33 and 1883/84 in which neither TRW nor MXD exhibit negative anomalies. The eruptions of Tambora in 1815 (Oppenheimer 2003) and Laki in 1783 (Thordason and Self 1993) had only moderate and almost no effects on the formation of BRs in the Pyrenees, respectively (table S1). These findings do not contradict our understanding of the spatial extent of the post-Tambora ‘year without a summer’ that was most pronounced in central Europe but less over the Iberian Peninsula (Trigo *et al* 2009, Büntgen *et al* 2017b), as well as the climatic effect of Laki (D’Arrigo *et al* 2011, Schmidt *et al* 2012) that had almost no effect on the formation of MXD in the Pyrenees (Büntgen *et al* 2017b). The highest concentration of 85% BRs occurs in 1698 CE. This distinct wood anatomical anomaly at the end of the 17th century likely resulted from a cluster of yet unidentified tropical eruptions (Sigl *et al* 2015, Toohey and Sigl 2017), and is corroborated by bi-polar sulphur ice core peaks in 1695/96 (Irawan *et al* 2009). The cold summer of 1698 in the western Mediterranean basin also corresponds with catastrophic famine and unprecedented mortality in Scotland (D’Arrigo *et al* 2020). The occurrence of two consecutive BRs in 1345 and 1346, which is a very rare phenomena in our new timeseries (table S1), coincides with the onset and establishment of the Black Death (Ziegler 1969, Twigg 1984); Europe’s most devastating plague pandemic caused by *Yersinia pestis* (Stenseth *et al* 2008, Schmid *et al* 2015).

Based on their sensitivity to abrupt cooling of several weeks or even days during the growing season, BRs offer a new high-resolution archive for refining the dating of ice core records. We consider BRs can improve the dating accuracy of past volcanic eruptions, because they can capture very short cold spells and are not affected by biological memory, a condition indicative of TRW (Frank *et al* 2007, Franke *et al* 2013). Moreover, BRs can help to identify possible short-term associations between volcanism, weather and society. We are also convinced that BRs are skilful for disentangling the volcano-climate-human nexus on sub-seasonal time-scales, because

agricultural productivity, and thus societal vulnerability, can depend on short-term weather extremes (Brázdil *et al* 2005, Battipaglia *et al* 2010), which are generally not captured in variations of the more classical TRW and MXD parameters. The fact that differences exist in climate responses to volcanic eruptions—both in space and in time—underlines the benefit of combining evidence from different tree-ring parameters (Büntgen 2019). Achievements at the interface of quantitative wood anatomy and dendroclimatology are expected to improve the spatial coverage of BR records for the past millennium in both hemispheres, and even over the past 2000 years at a few sites. The combined, high-resolution, wood anatomical and dendrochronological insights should be compared against spatiotemporally explicit early instrumental and documentary evidence to gain deeper understanding of the timing and climatic forcing of yet unidentified eruptions and their source volcanos, such as the eruption(s) in 1345(6) that likely caused cooling at the onset of Europe’s Black Death, or the possible cluster of eruptions between around 1808 and 1813 that possibly added to the exceptional temperature depression in the aftermath of the Tambora eruption in 1815 CE. In case of the 1808–1809 mystery eruption (Dai *et al* 1991, Chenoweth 2001, Cole-Dai *et al* 2009, Guevara-Murua *et al* 2014), our wood anatomical evidence would suggest that cooling reached the Pyrenees before November, because late-wood formation and subsequent cell wall lignification are known to occur between September and October when high-elevation pines in the central Spanish Pyrenees recycle non-structural carbohydrates from the beginning of the growing season in May and June (Camarero *et al* 1998, Büntgen *et al* 2017b).

Last but not least, we encourage intensified efforts to improve our understanding of the physiological mechanisms behind the lignification process in plant cell walls (Meents *et al* 2018), and of the possible connections between cell wall lignification and temperature (Piermattei *et al* 2015, Crivellaro and Büntgen 2020, Tardif *et al* 2020). The feasibility of such work, however, critically depends on the quality and availability of both, suitable wood samples, as well as *in situ* meteorological measurements.

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## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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