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Tree ring effects and ice core acidities clarify the volcanic record of the first millennium

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Supplementary: Are bristlecone pine frost rings good indicators of large climatically effective volcanic eruptions?

In this paper we use frost damage rings in bristlecone pine as an indicator of large volcanic eruptions. By comparing the space intervals between these frost rings with the space intervals between volcanic acid layers in ice cores, we show that the GICC05 timescale as well as the dating of ice cores from Antarctica appear to be misdated by approximately 7 years in the 1st millennium AD, with the ice dates being too old. A natural question is whether frost rings are a valid proxy for climate dislocation due to explosive volcanism? Here we demonstrate the validity of using frost rings as markers for large, climatically effective, volcanic eruptions. Noting that in recent centuries good correlation exists between frost ring dates and both dates of historical eruptions, and dates of significant hemispheric cooling as evidenced by temperature reconstruction from Maximum Latewood Density (MXD) in North European trees.

Using MXD measurements from a series of tree ring chronologies Briffa et al. (1998) created a time-series of reconstructed Northern European temperatures from AD 1400 to AD 1990, listing the 30 coldest years in this period (Briffa et al., 1998, Table 1). It is apparent from this list that cold climate shifts occur in the year of, or the years immediately after, large volcanic eruptions in recent centuries.

In Table 1, below, we examine the period between AD 1400 - 1900, listing a) the most widely known historical explosive volcanic events (Siebert et al., 2011), b) the years of most severe cold noted by Briffa et al. (1998), c) years for which frost rings have been recorded by LaMarche and Hirschboeck (1984) and Salzer and Hughes (2007) in bristlecone pines, and d) the start years for volcanic acid in the NEEM S1 and WDC06A cores (Sigl et al., 2013). In the Table we see that the spacing between the various related phenomena are highly consistent. This is a clear and unambiguous indicator that large volcanic eruptions can lead to climatic dislocation, with cold temperatures being observed in Northern Europe in years of, or just after, major volcanic eruptions. Furthermore, these large climatically effective eruptions seem capable of producing climatic conditions that result in frost damage in North American bristlecone pines. This demonstrates that bristlecone pine frost rings can be a useful indicator of significant volcanic eruptions.

If we perform a similar version of this same exercise, but this time taking the most significant historical dust veil events as noted by Stothers and Rampino (1983) in the period from 100 BC to AD 700 (see Table 2), we see that frost rings show identical spacing, as do major ice acid layers in both the GICC05 and NEEM S1 records. However, while the respective spacing is highly consistent, the dates show that the ice acidities are systematically offset from *both* the historical and frost ring dates by close to 7 years. While we concentrate in the main article only on frost rings, we can also inspect MXD and tree-ring width chronologies to support the hypothesis. Inspecting other independent tree-ring chronologies, we do indeed observe evidence for environmental stress and/or reduced temperatures (manifesting as narrow rings or reduced MXD) for the years 44-42 BC, AD 536/7 and AD 626/7 (Grudd et al., 2002; Esper et al., 2012, 2014; Jones et al., 2013; Melvin et al., 2013), thereby strengthening the association of frost-ring occurrence in bristlecone pines with hemispheric cooling due to explosive volcanism.

We acknowledge in the text that there is no one-to-one relationship between frost rings and volcanic eruptions. To elaborate, it is possible to have frost rings without any apparent causal eruption; such frost rings likely occurring through natural and localised climatic or environmental variation. However, it is equally possible to note some cold years, as reconstructed from MXD measurements, with no volcanic cause. There are some cases where a large volcanic event produces apparent hemispheric cooling but without frost ring formation. Such a case occurs with the 1783 Laki eruption, which has the largest acid signal in the NEEM S1 ice core during the last two millennia (Sigl et al., 2013). However, Briffa et al. (1998) rank the year 1783 as only the 26th coldest in the last 600 years, which suggests that while the Laki eruption may have produced a large amount of acid, its contribution to climate forcing may not have been significant enough to induce bristlecone pine frost damage. However the evidence presented in Tables 1 and 2 argues persuasively that bristlecone pine frost rings can and should be considered as useful markers for large volcanic eruptions.

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Table 1. Dates of large historical eruptions (Siebert et al., 2011) within the last 600 years that likely caused significant Northern Hemisphere negative temperature anomalies as noted and ranked by Briffa et al., (1998). Bristlecone pine frost rings as recorded by LaMarche and Hirschboeck (1984)(†) and Salzer and Hughes (2007)(‡), are also listed, as are the start years of large ice acid signals (deposition SO_4^{2-} in units of Kg/km^2 are given in parentheses) observed in the NEEM S1 and WDC06A ice cores Sigl et al. (2013). Space analysis between successive phenomena (highlighted in bold) shows high consistency, and that large volcanoes can induce frost damage in bristlecone pines.

Historical date	Cold year (rank)	Temperature anomaly °C	Frost Ring	NEEM S1 (SO_4^{2-})	WDC06A (SO_4^{2-})
1883	1884 (13)	-0.34	$1884^{\dagger\ddagger}$	1884 (11.2)	1883.6 (18.5)
47	**47-48**		**47**	**48.3**	**48.9**
1836	1836 (21)	-0.29	$1837^{\dagger}$	1835.7 (13.1)	1834.7(15.1)
	1837 (11)	-0.32			
21	**20-21**		**20**	**20.1**	**19.3**
1815	1816 (2)	-0.51	$1817^{\dagger}$	1815.6 (39)	1815.4 (88.6)
	1817 (5)	-0.44			
175	**175-176**		**177**	**174.5**	**173.8**
1640	1641 (3)	-0.50	$1640^{\dagger\ddagger}$	1641.1 (46.8)	1641.6 (12.4)
39	**40**		**39**	**40.7**	**40.6**
1601	1601 (1)	-0.81	$1601^{\dagger\ddagger}$	1600.1 (30.4)	1601.4 (24.0)
148	**148**		**148**	**147.0**	**148.0**
1453	1453 (4)	-0.50	$1453^{\dagger\ddagger}$	1453.1 (21.6)	1453.4 (8)

Table 2. Historical dust veil events as noted by Stothers and Rampino (1983) in the period from 100 BC to AD 700, compared with bristlecone pine frost rings as recorded by LaMarche and Hirschboeck (1984)(†) and Salzer and Hughes (2007)(‡) and observation of ice acid in the GICC05 and NEEM S1 timescales (Sigl et al., 2013). Space analysis demonstrates that while there is a high consistency between phenomena spacing (highlighted in bold), ice core dates are offset by approximately 7 years.

Historical dust veils	Frost rings	GICC05	NEEM S1
626	$627^{\dagger}$, $628^{\ddagger}$	619±2	619.1
90	**91**	**90**	**89.3**
536	$536^{\ddagger}$	529±2	529.8
580	**580**	**579**	
44 BC	43 BC†‡	50±1 BC	N/A