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Volcanic cooling signal in tree ring temperature records for the past millennium

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[1] Tree rings are an important proxy for understanding the timing and environmental consequences of volcanic eruptions as they are precisely dated at annual resolution and, particularly in tree line regions of the world, sensitive to cold extremes that can result from climatically significant volcanic episodes. Volcanic signals have been detected in ring widths and by the presence of frost-damaged rings, yet are often most clearly and quantitatively represented within maximum latewood density series. Ring width and density reconstructions provide quantitative information for inferring the variability and sensitivity of the Earth's climate system on local to hemispheric scales. After a century of dendrochronological science, there is no evidence, as recently theorized, that volcanic or other adverse events cause such severely cold conditions near latitudinal tree line that rings might be missing in all trees at a given site in a volcanic year ("stand-wide" missing rings), resulting in misdating of the chronology. Rather, there is a clear indication of precise dating and development of rings in at least some trees at any given site, even under adverse cold conditions, based on both actual tree ring observations and modeling analyses. The muted evidence for volcanic cooling in large-scale temperature reconstructions based at least partly on ring widths reflects several factors that are completely unrelated to any misdating. These include biological persistence of such records, as well as varying spatial patterns of response of the climate system to volcanic events, such that regional cooling, particularly for ring widths rather than density, can be masked in the large-scale reconstruction average.

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1. Introduction

[2] In this article, we review some of the evidence for the cooling effects of major volcanic eruptions over the past millennium, with an emphasis on tree ring data networks for northern tree line locations, and the interpretation of the volcanic signal in large-scale temperature reconstructions based largely or entirely on these data [e.g., *D'Arrigo et al.*, 2006, hereafter DWJ06]. In so doing, we also counter the assertions of *Mann et al*. [2012a, 2012b, hereafter MFR12a] that northern tree ring records used in such large-scale reconstructions have been misdated due to unaccounted-for stand-wide "missing" rings in a sizeable fraction of the sites studied during three major volcanic events of the past millennium (1258, 1453, and 1816). Missing rings occur during adverse environmental conditions when one or more trees at a given site do not lay down wood from cambial activity. Such rings are accounted for in the cross-dating process [*Fritts*, 1976]. Errors regarding MFR12a's tree-growth modeling are addressed in detail elsewhere [e.g., *Anchukaitis et al*., 2012a].

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2. Tree Ring Proxies of Volcanic Cooling

[3] Tree rings have been used successfully for nearly a century to reconstruct past climate variability prior to the instrumental era [e.g., *Hughes et al*., 2011]. Tree rings have higher dating precision than most other proxy archives due to the cross-dating method, which ensures accurate dating resolution to the exact year of formation [*Fritts*, 1976; *Schweingruber*, 1988]. When reconstructing past temperatures, dendrochronologists sample trees at latitudinal and elevational tree line forest locations where tree growth is predominantly temperature limited. On interannual to decadal time scales, volcanically forced cooling is a key source of temperature variability [*Robock and Oppenheimer*, 2003] and can be recorded in tree ring records over the past millennium or in a few cases even earlier [e.g., *LaMarche and Hirschboeck*, 1984; *Jacoby et al*., 1999; *D'Arrigo et al*., 2001; *Hegerl et al*., 2003, 2007; *Salzer and Hughes*, 2007].

[4] Several tree ring parameters have been used to study past volcanic events from temperature-sensitive sites at tree line. One of these is ring width (RW), the annual increments of the growth rings in wood. Trees typically respond to volcanically forced cooling and other adverse events in tree

line settings by producing narrow ring widths (as well as sometimes so-called frost rings, see below), very narrow "microrings," or missing (sometimes locally absent) rings. Because biological persistence in tree line conifers causes RW to exhibit high year-to-year autocorrelation [*Frank et al*., 2007; *Anchukaitis et al*., 2012a], cooling caused by volcanic eruptions can appear to persist for several years within temperature reconstructions based on RW. It is well known from the literature that RW can thus potentially underestimate the abruptness and severity of climatic extremes due to volcanic cooling, and that the biological consequences and therefore climate response can at times appear to be lagged over several years [*D'Arrigo et al*., 1992; *D'Arrigo and Jacoby*, 1999; *Krakauer and Randerson*, 2003; *Frank et al*., 2007]. Thus, although useful in various ways for studying the effects of volcanism on past climate, RW is not the most appropriate parameter for quantitative, large-scale analyses of volcanic cooling and related estimates of the Earth's climate sensitivity on *interannual* time scales over the past millennium [*D'Arrigo et al*., 2009; *Anchukaitis et al*., 2012a].

[5] "Frost rings" are annual growth rings in the wood that contain visible cellular damage due to often sudden and adverse cold events such as those following a substantial volcanic eruption (or other extreme conditions [e.g., *Stahle*, 1990]), and in some settings and tree species there is a strong link between frost rings and volcanic episodes. This has been perhaps best demonstrated using the long-lived bristlecone pines in the southwestern USA, where there is strong agreement between the presence of frost rings and volcanism [*LaMarche and Hirschboeck*, 1984; *D'Arrigo et al*., 2001; *Salzer and Hughes*, 2007].

[6] Frost damage, for example, has been observed in a widespread, severe cooling event in AD 536, presumed to have been caused by a large volcanic eruption. This event has been dated precisely in independent tree ring records from around the globe from frost-damaged, narrow, or light density rings (e.g., in Taymir, and in Mongolia [*D'Arrigo et al*., 2001]; and the southwestern USA [*Salzer and Hughes*, 2007]; Europe [*Baillie*, 2008]; and even in the Southern Hemisphere (Chile [*Lara and Villalba*, 1993]; *Larsen et al*. [2008] note this event in ice cores but dating is less certain than for tree rings). This synchronicity is a strong indication that there are no chronological errors in these series over the past two millennia, as was erroneously suggested by MFR12. This precise agreement illustrates the accuracy of tree ring dating and would not be observed if there were rings that were missing on a stand-wide basis at a sizeable fraction of sites following certain major volcanic eruptions.

[7] Thus far, the strongest and most consistent tree ring proxy for past volcanic events is the maximum latewood density parameter (MXD), which can show a strikingly clear response to volcanically induced summer cooling (Figure 1) [*D'Arrigo et al*., 1992; *D'Arrigo and Jacoby*, 1999; *Briffa et al*., 1998], without the lagged or dampened after-effects seen in ring width from the same trees [*Frank et al*., 2007]. For example, the *Briffa et al*. [1998] circumboreal tree ring network of 383 MXD chronologies, processed to emphasize high-frequency changes in NH growing season mean temperature, shows notable, precise correspondence with the timing of explosive volcanic eruptions (Figure 1) (modified from *Anchukaitis et al*. [2012a]). Regarding MXD, this striking correspondence between MXD negative extremes and the timing of volcanic events as indicated in the forcing time series is a clear indication of the absence of smearing due to misdating. Note, however, the dampened response of RW data (Figure 1c; see also later Figure 4). *Briffa et al*. [1998] state: "the breadth of temperature sensitivity and firm dating control in our data provide as rigorous a basis for examining the nature of a volcano/temperature link as any achieved to date." This sensitivity in MXD as opposed to the coeval RW to such extreme high-frequency events is potentially explained by the fact that RW formation is more likely to draw on stored reserves from the prior growing season and to reflect the cumulative cambial activity in the wood over the growing season, while MXD, primarily a product of cambial activity during late summer, is more immediately responsive to cooler conditions and possibly other environmental effects coincident with volcanic episodes. Figure 1 illustrates definitively that MXD is a more appropriate parameter than RW for performing quantitative analyses of volcanic effects on climate. Despite evidence of robust temperature sensitivity and a strong and stable response to cooling, however, MXD time series are very labor intensive and expensive to produce, undergo substantial attrition in processing (as only a subset of wood samples are typically in a usable condition for MXD analysis from a given site), and have not been successfully generated from all tree species used in dendrochronology. As a consequence, relatively few such chronologies have been produced as compared to RW for use in local, regional, and hemispheric-scale temperature reconstructions, and focused effort and funding are needed for the dendrochronological community to process additional long (millennial and near-millennial) tree ring series for MXD. Although the cooling signal in MXD is clearly apparent, there are additional factors that could potentially lead to overestimation of volcanic cooling, such as acid haze or other conditions that can block sunlight and slow photosynthesis and lignification [*Kalela-Brundin*, 1997; *Thordarson and Self*, 2003]. These potential influences have not yet, however, to our knowledge been explicitly identified in actual MXD chronologies.

3. Evidence for Volcanism in Long Instrumental and Historical Records

[8] The impacts of major volcanic events on climate have been previously documented in long instrumental records for Europe, notably for Fennoscandia, central Europe, and central England [e.g., *Jones et al*., 2003], and more sparsely for the USA and some other locations. However, there are only nearly three to five volcanic events per century, significantly limiting the information that can be gleaned from such data.

[9] There also exists a long (> 500 years), exactly dated documentary Dutch reconstruction for the Low Countries [*van Engelen et al*., 2001]. With respect to 1258 and 1453, the two earliest major volcanic events cited in MFR12, *van Engelen et al*. [2001] show that the summer of 1453 was not particularly unusual, while 1258 was in the coldest of their three categories. Noteworthy, however, is that there were other summers in the 1300s and 1400s classified as being extremely cold (colder than either 1453

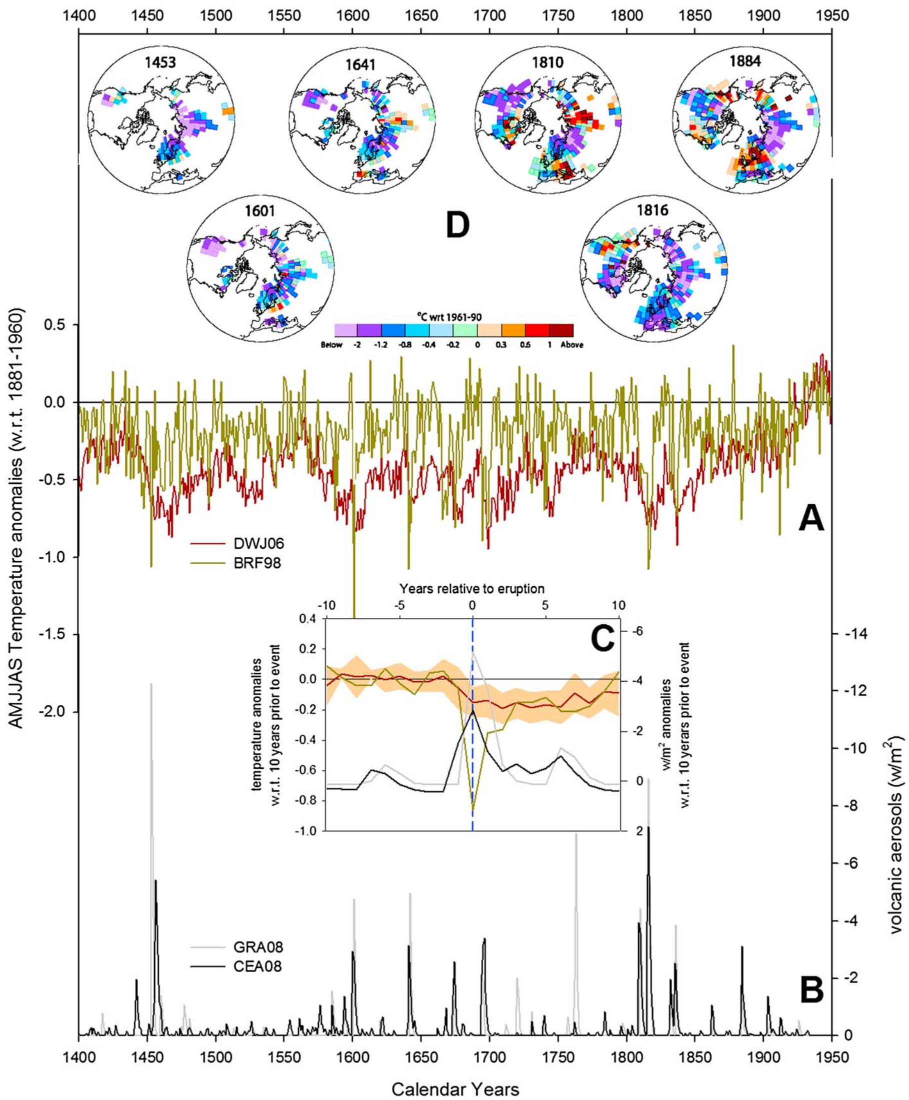

Figure 1. Figure modified from *Anchukaitis et al*. [2012a], comparing RW and MXD spatial variability plots, and volcanic forcing series. (a) DWJ06 and *Briffa et al*. [1998, BRF98] Northern Hemisphere reconstructions. Each series has been scaled to extratropical (20°N–90°N) April–September mean temperatures [*Brohan et al*., 2006] over the 1881–1960 period. NB. DWJ06 was originally calibrated to annual temperatures, but the constituent TR records are all summer temperature proxies, justifying this recalibration [see also *Wilson et al*., 2007]. (b) Volcanic aerosol indices (w/m^2) of *Gao et al*. [2008] (GRA) and *Crowley and Unterman* [2012] (CEA). (c) Superposed epoch analysis of six major volcanic events 1453, 1601, 1641, 1810, 1816, and 1884. Mean values are expressed as anomalies relative to the mean of the 10 values before the event. Two-sigma error is only presented for the DWJ06 data. (d) Spatial anomaly (w.r.t. 1881–1960) maps of reconstructed April–September mean temperature using the BRF98 MXD network [*Briffa et al*., 2002].

or 1816) with no apparent volcanic cause. The Central England temperature series (extending back to 1659) includes at least two summers (1695 and 1725) that are colder than the so-called "year without a summer" of 1816. These are classified in the coldest category in the long Dutch series, whereas 1816 is only in the second worst category (of 9) and is thus not the coldest summer in these long temperature records. Thus, we would like to emphasize that not all cold summers at a particular location are related to volcanic events, and not all volcanic years produce a cold summer [e.g., *Schneider*, 1983]. However, whatever the reasons for a cold year, temperature-sensitive tree ring chronologies clearly track long temperature records very well in some regions (see below).

4. Large-Scale Temperature Reconstructions and Volcanic Cooling

[10] The long instrumental records outlined above are limited largely to Europe and are in any case not of sufficient length (with the exception of the cited Dutch documentary record) or global distribution to obtain a comprehensive

understanding of the climatic impacts of volcanic events, which is why tree ring records have proven useful in this regard. Ring width chronologies have been overwhelmingly used to generate tree ring-based hemispheric-scale summer and annual temperature reconstructions (Figure 1) [e.g., *Esper et al*., 2002, DWJ06]. These large-scale temperature reconstructions do show cooler inferred values coincident with volcanic eruptions (Figure 1), although such RW composites, as noted above, tend to have a smoother response to eruptions than MXD, most likely due to lagged effects of previous year conditions on tree growth [*Krakauer and Randerson*, 2003; *Frank et al*., 2007; *Anchukaitis et al*., 2012a]. Large-scale reconstructions based largely or entirely on RW were initially conceived mainly to better understand the low-frequency (multidecadal and longer time scale), large-scale variability of the Earth's climate system over the past millennium. However, reconstructions such as DWJ06 are well known to be less reliable for making inferences about the global mean climate response at annual to interannual time scales, such as those associated with high-frequency volcanic episodes. This fact is related to (1) the rather short duration of the volcanic atmospheric perturbation, typically less than 3 years [e.g., *Bradley*, 1988], (2) the potential for spatial and temporal heterogeneities of both the volcanic response [*Robock and Mao*, 1995] and particularly the generally sparse tree ring data networks [*Anchukaitis et al*., 2012a], and (3) the greater number of proxy locations likely to be necessary to characterize the global interannual temperature signal, in contrast to large-scale multidecadal to centennial variations [e.g., *Jones et al*., 1997; *Zorita et al*., 2003; *Jones et al*., 1998; *North et al*., 2011]. In fact, DWJ06 specifically noted that there is "little coherence between the reconstructions and instrumental data at *interannual* time scales" and that optimal coherence is found at time scales >20 years. Whether this holds true for individual and potentially extreme interannual-scale forcing such as that associated with large tropical volcanic eruptions is less well known, but observations and modeling of associated summer temperature anomalies [e.g., *Kirchner et al*., 1999; *Collins*, 2003; *Robock*, 2003; *Shindell et al*., 2003] indicate that the summer temperature response to eruptions varies spatially, due in part at least to internal climate system variability such as ENSO. Further, *Anchukaitis et al*. [2012a] have demonstrated that GCMs may simulate a summer temperature field with distinct regions of summer warming following even apparently large eruptions like that in 1258, despite a strong tendency toward overall global and hemisphere mean summer cooling.

5. The Postulated "Diffuse Effect" in Tree Rings

[11] It has been suggested [*Robock*, 2005, MFR12a] that growth enhancement due to increased diffuse light availability might further mute the volcanic signal as represented in large-scale tree ring reconstructions, as this would enhance photosynthesis, and presumably augment basal growth. Enhanced photosynthesis due to increases in diffuse light has been inferred from eddy covariance measurements in closed canopy, mixed hardwood forests [*Gu et al*., 1999, 2003]. However, any effect on basal growth from this phenomenon appears to be absent in the global tree ring network analyzed by *Krakauer and Randerson* [2003], who observe that "Our findings suggest that for extratropical trees, any diffuse light growth enhancement is offset by other, deleterious consequences of eruptions, such as summer cooling and a decrease in the length of the growing season." In the open, conifer-dominated tree line environment from which temperature-sensitive tree ring chronologies are mostly developed, the effect modeled by *Gu et al*. [2003] may be less important for productivity [*Krakauer and Randerson*, 2003]. Another explanation is that any increases in photosynthesis do not translate simply into enhanced stem growth [*Rocha et al*., 2006; *Vaganov et al*., 2006]. More research is needed to test this theory both in the temperate forests for which it was postulated, as well as at tree line sites where temperature-sensitive tree ring chronologies are developed. This might be accomplished using carbon isotopes, or the study of cloud/sunshine effects [e.g., *Gagen et al*., 2011] and the use of forward tree-growth models.

6. Spatial Variability of Volcanic Cooling

[12] The considerable spatial variability in the dynamical response of the earth's climate system to volcanic eruptions is well illustrated in instrumental observations [*Robock and Mao*, 1992; *Kirchner et al*., 1999; *Collins*, 2003; *Jones et al*., 2003; *Robock*, 2003], tree rings [*D'Arrigo and Jacoby, 1999*; *Briffa et al*., 1998, 2002], and modeling studies [e.g., *Shindell et al*., 2003, 2004; *Timmreck et al*., 2009; *Anchukaitis et al*., 2012a; *Zhang et al*., 2013]. Depending on the nature of the eruption, the magnitude of the resulting change in incoming solar radiation, prevailing background climate and internal variability, season, latitude, and other considerations, such events can perturb the atmospheric wave pattern of the atmosphere, such that some regions of the globe will cool, while others will experience no significant change or even warm (Figure 1) [e.g., *Robock and Mao*, 1992].

[13] When tree ring chronologies (particularly those derived from RW) from these various regions are averaged together to produce hemispheric temperature reconstructions, the hemispheric or global volcanic signal could be muted depending on the local response at the site of the available chronologies and the distribution of all sites with respect to those experiencing the greatest cooling (e.g., Figure 1), and this is compounded by the importance of biological persistence and year-to-year autocorrelation in the RW proxy. In the case of MXD, the volcanic signal appears to remain more distinct in the large-scale average, most likely due to the overall strength of temperature signal in this parameter and the lesser degree of biologically based autocorrelation [*Briffa et al*., 1998; *D'Arrigo et al*., 2009]. Spatial analysis of the well-distributed *Briffa et al*. [1998, 2002] MXD network also illustrates considerable spatial variability (Figure 1d).

[14] An MXD-based summer temperature reconstruction for Alaska shows an anomaly in 1783 that is more than four standard deviations below the mean following the eruption of Laki, Iceland, which coincided with massive famine for local Inuit Alaskan populations (Figure 2) [*Jacoby et al*., 1999]. Other internal factors (including combined negative North Atlantic Oscillation, and El Nino-Southern Oscillation warm episodes) also likely contributed to cooling in the winter following Laki, but not in all locations of the Northern Hemisphere (Figure 2) [*D'Arrigo et al*., 2011]. Similarly, cooling after the massive tropical eruption of Tambora in

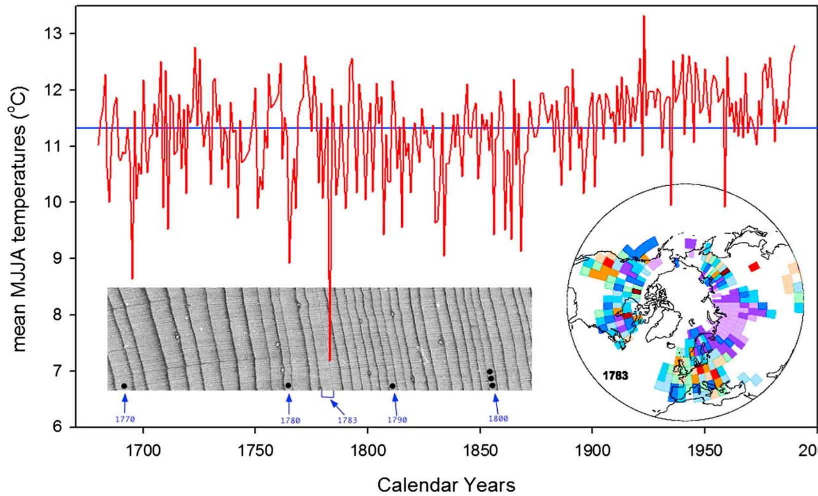

Figure 2. MXD-based Alaskan May–August temperature reconstruction, showing pronounced cold anomaly following the eruption of Laki, Iceland in 1783. Inset at lower left shows annual ring width increments in white spruce from Alaska. MXD measures the peak density value in the latewood of each year. Note very low density in 1783 in this wood section following the eruption of the Laki volcano in Iceland, corresponding to the reconstructed time series. Lower right, spatial anomaly (w.r.t. 1881–1960) plot from BRF98 MXD network [*Briffa et al*., 2002]. Figure modified from *Jacoby et al*. [1999].

1815, for which the subsequent year 1816 was known in eastern North America (and western Europe) as the "year without a summer" [*Stommel*, 1983], is evident in MXD data (see below) as the lowest value in the past ~400 years in Labrador [*D'Arrigo et al*., 2003] and the lowest in the last 1250 years in the Alps [*Buentgen et al*., 2006]. Yet, conditions were not unusually cold in all regions of the Northern Hemisphere (Figure 1) [*Briffa et al*., 1998, 2002].

[15] MFR12b claimed that long historical temperature data compiled by the Berkeley Earth Surface Temperature (BEST, http://berkeleyearth.org/) [*Rohde et al*., 2013] project showed global mean cooling in the early 19th century that, they posit, should have been detected by the tree ring network used by DWJ06. However, examination of the data available from the BEST database shows that (1) the BEST compilation for this time period is largely restricted to locations concentrated in western Europe, and that (2) summer temperature anomalies, even after Tambora's large and well-documented tropical eruption, were heterogeneous. This was the case even across the spatially limited instrumental domain (Figure 3; note that there are other temperature records not included in the BEST compilation (e.g., the long temperature series from Tornedalen [*Klingbjer and Moberg*, 2003]). Cooler temperatures prevailed in England and Scotland and throughout the Alpine region, as well as in Connecticut and apparently Iberia [*Trigo et al*., 2009], but in northern and eastern Europe and India temperatures were normal or even warmer than the prior year. These observations are verified by *Neumann* [1990], who observed that "the Baltic Region had not suffered from Tambora's eruption, unlike the lower mid-latitudes of Western and Central Europe." Contrary to the claim by MFR12b then, the BEST data actually support the observation that the response to even very large tropical volcanic eruptions varies in space, and therefore it is important to consider the precise distribution of proxy data (those for DWJ06 were only approximated in MFR12a) relative to the pattern of temperature anomalies when seeking to interpret the tree ring record. Much care is therefore needed when working with large-scale composite series due to such spatial variability. Ultimately, the ideal approach would be to use spatial field reconstructions based on MXD, but as noted this is difficult due to the limited number of appropriate MXD records at present, and the inevitable decline in availability of such series back in time [*Briffa et al*., 1998].

7. Volcanically Induced Missing Rings and Implications for the Accuracy of Tree Ring Dating

[16] In extreme cases of adverse cold conditions, as following the aforementioned eruption of Tambora, a growth ring may be missing within or among one or more trees at a given location, and such missing rings are observed on occasion at tree line and are accounted for in the cross-dating process [*Cook and Kairiukstis*, 1990]. However, it is quite rare for more than ~5–10% of the samples from trees at a given northern latitude site to have a missing ring in such a year [*St. George et al*., 2013], and it is extremely unlikely that this percentage will ever reach anywhere near 100% missing rings at any individual tree line site, even for very cold postvolcanic episodes, as was suggested by MFR12a. Widespread missing rings at individual sites are actually more prevalent in drought-prone settings [*St. George et al*., 2013]. Temperature-sensitive tree ring series seldom have missing rings.

[17] In an analysis of the tree ring data network of DWJ06, the maximum percent missing rings in any of the 19 regional chronologies compiled for this paper for northern latitudes (with the exception of one regional data set for which missing ring information was not available) were found for the coastal Alaskan composite, where 14% of the tree samples have a missing ring in 1699, part of a cluster of several low density and RW marker years, beginning in 1695, linked to a presumed but unknown volcanic eruption (Figure 1) [*Briffa et al*., 1998]. There are no instances in DWJ06 of

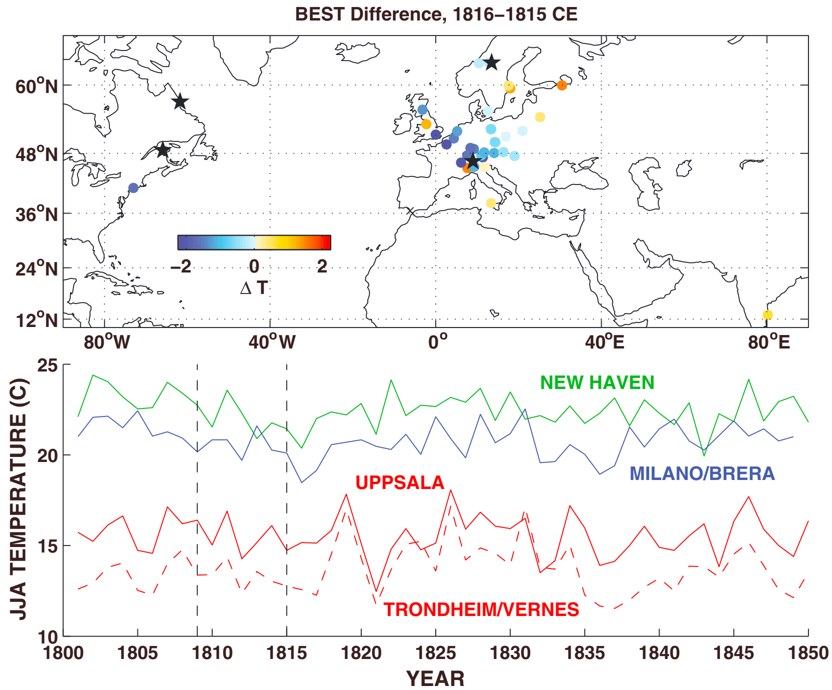

Figure 3. Historical observational temperature variability associated with the 1815 Tambora eruption. Top panel: Year-to-year temperature change (1816–1815) for historical meteorological data from the Berkeley Earth Surface Temperature (BEST, http://berkeleyearth.org/) [*Rohde et al.*, 2013] project database. We selected and plotted all stations spanning at least 1800 to 1850 and with fewer than 10% missing data ($n = 38$). Plotted as black stars are the composite tree ring chronology sites used in DWJ06 in Quebec, Labrador, Jaemtland (Sweden), and the Alpine region. The other 15 sites are not shown, as they are not in the map domain and are not colocated with any of the stations compiled by BEST. Bottom panel: Summer instrumental temperature time series from stations compiled by BEST that are nearest to the DWJ06 chronologies in the mapped domain, showing the evolution of local climate in the early 19th century. Dashed lines show the timing of two eruptions (1809 and 1815).

the percentage of missing rings exceeding 14% at any of the other regional sites over the past millennium. In fact, ~100 years of tree ring science has identified no evidence that adverse climatic events can cause such severely cold conditions that no rings at all might form at any of the trees at a given northern site, resulting in misdating of the final chronology, as suggested by MFR12a. Even assuming MFR12 were correct, we would expect to see a gradation of missing rings increasing for colder reconstructed years. It is highly unlikely to expect a jump from a maximum of 14% missing rings at a given site to a complete absence of rings in a regional series without some intermediate instances of high percentage years in between.

[18] Rather, based on both tree ring observations and modeling analyses [*Anchukaitis et al.*, 2012a], there is clear evidence of precise dating and laying down of rings in some trees even under extremely severe cold conditions. Tree ring data have also been shown to cross-date along transects from upper elevational (temperature-sensitive) to lower forest border (moisture-sensitive) coniferous tree lines in the southwestern USA [e.g., *LaMarche*, 1974], indicating that there are no unaccounted-for stand-wide missing rings.

[19] The only published previous claim of stand-wide missing rings for northern tree line, of which we are aware, is a study by *Earle et al*. [1994]. They speculated that a ring was "globally missing" for all the larch trees growing at a site near the Kolyma region of northeastern Siberia in 1816, following the eruption of Tambora. The basis for their premise was that the Kolyma ring width chronology correlates over much of its length with another chronology from the Polar Urals (3800 km west of their study site), which showed a very narrow ring in 1816. This led them to infer a missing ring in the Kolyma chronology in 1816, and to insert a zero value for that year. However, other chronologies from the region have shown that the 1816 ring was not missing (G. Jacoby, personal communication, 2012), indicating that cold in this region at this time was not exceptional, and illustrating the spatial nature of volcanic cooling. Comparison with these and other additional tree ring data from the region led Earle to retract his hypothesis (C. Earle, ICF Jones & Stokes, personal communication, December 2012: Dear Colleagues Letter of 24 May 1994, "The 1816 ring is *not* missing," italics ours; and "trees around the Northern Hemisphere displayed widely varying responses to the Tambora eruption"). This case also illustrates the potential hazard of assuming that a particular large-scale signal should necessarily be expected to be reflected in a specific chronology.

[20] MFR12a concluded, based solely on results from a tree-growth model, that the Tambora event is one of two or three cases (others are eruptions in 1258 and 1453) where

stand-wide missing rings supposedly occurred in a sizeable fraction of tree ring sites at northern tree line over the past millennium. The MFR12a model suggests that for 1816, the most recent of the three eruptions, and the only one for which there are instrumental data available for comparison, fully half of the 19 regional sites in DWJ06 should be expected to have stand-wide missing rings, a suggestion that we address further in the next section.

8. MXD Records in the "Year Without a Summer" in 1816

[21] Of the 19 regional RW sites in DWJ06, one of these, from latitudinal tree line in Labrador, eastern Canada, has a corresponding composite MXD regional chronology derived from the very same samples from which the RW data were measured, so that their dating matches precisely. This region was one of those that experienced the "Year Without a Summer" in eastern North America [*Stommel*, 1983; *Harington*, 1992], and it shows the lowest MXD value in the past several centuries, >4.5 standard deviations below the long-term mean, in 1816 (Figures 4a and 4b).

[22] The calibrated anomaly coincides well with the most severely cold value on record in the New Haven, Connecticut, USA summer temperature series, one of the very few long instrumental series for the eastern coast of North America for 1816, albeit far to the south of the Labrador tree ring site (Figure 3). Further, the sea ice duration (SID) record for Hudson Bay, Canada [*Catchpole and Faurer*, 1985] shows 1816 as the most extensive sea ice year over the entire length of record (Figure 4a).

[23] Note also that if the year 1816 did in fact show a stand-wide missing ring in Labrador, then the extremely low value actually observed would have to instead represent 1815, which was not a particularly cold year by comparison, according to both the New Haven instrumental record and the Hudson's Bay ice record (Figure 4a). In fact, correlations prior to 1816 between the MXD data and both the New Haven and SID records are entirely consistent with the post-1816 correlations (Figure 4a), indicating that the pre-1816 period in the tree rings is correctly dated and not offset in any way. We surmise that in all of the Northern Hemisphere, one of the regions most likely, in theory, to show a stand-wide missing ring in 1816 would be at latitudinal tree line in Labrador, on the eastern coast of North America, during the year without a summer. Yet it is clear from Figure 4a that this is not the case. We further note the dampened response of the Labrador RW data compared to the MXD series (Figure 4c).

[24] On the other side of the North Atlantic, and at a similar latitude to Labrador, tree ring data sets from the Cairngorm Mountains in the Scottish Highlands [*Hughes et al*., 1984; *Wilson et al*., 2012] similarly show no evidence for a country-wide missing ring in 1816 (Figures 4d and 4e) using a regionally based composite of MXD. As the early Edinburgh instrumental record dates back to 1764 (see discussion in *Jones and Lister* [2004]), it is possible to quantify the coherence between the tree ring and instrumental data on either side of 1816. As discussed for Labrador above, if the 1816 tree ring was missing from all Scottish trees, then the correlation would break down. For the 52 year period from 1816 to 1867, MXD correlates with JJA mean temperatures at 0.60. Prior to 1816 (1764–1815), the correlation is 0.34. Although the correlation between MXD and growing season climate is weaker for this earlier period, this likely reflects both the markedly weaker replication in the MXD records in the 18th century as well as management-related disturbance in these woodlands through the 18th and early 19th centuries [*Wilson et al*., 2012]. Inserting a missing value at 1816 for both the Labrador and Scottish TR series and effectively shifting them back by one year result in correlations less than zero for the pre-1816 period. Again, comparison of the Cairngorm RW and MXD regional chronologies (Figure 4f) clearly shows that MXD portray a stronger response to Tambora than the RW data.

[25] Further evidence refuting the hypothesis of MFR12a is described by *Esper et al*. [2013]. They compare long instrumental and historical data for northern and central Europe with MXD records (from some of the same corresponding RW sites and derived from the same rings as those used in DWJ06) and show that there is no offset between the records prior to 1816, as one would expect if the real 1816 value were missing and the chronologies were misdated. Based on the above evidence, we reject the hypothesis of MFR12a that there are unaccounted-for missing rings at these European sites, which represent additional "year without a summer" locations where, according to the argument from MFR12, we would most expect them to be found.

[26] For the MFR12a theory to be considered valid, it must explain which other sites or regions from DWJ06 or other northern tree ring data sets might be more likely to have an unaccounted-for stand-wide missing ring than the locations cited above. As noted, these locations just discussed are from the areas where historical observations indicate the most impact by the year without a summer on both sides of the North Atlantic, following the eruption of Tambora. We contend that in some other regions, tree ring data may not show an unusually cold year in 1816, not because it is missing (on a stand-wide basis) at these locations, but because of the variability of response to volcanic events across space (see above) resulting from the dynamical response of the Earth's climate system to volcanic eruptions.

9. 1258: Comparisons of Juvenile Versus Old Growth Wood

[27] Addressing whether there is a stand-wide missing ring for 1258 is more of a challenge as there are no instrumental records or no robust annually resolved historical proxy records for this period. Indeed, the tree ring proxy network is much more sparse in this epoch in general. One possible approach to address this issue is to compare juvenile and mature growth indices for the same year. Due to the wider rings expressed in juvenile growth relative to when a tree is mature, it can be rare for a tree to express a missing ring in its first few decades of life. Using the RW and MXD data from the Icefields reconstruction [*Luckman and Wilson*, 2005], another of the site chronologies utilized in DWJ06, we extracted trees that were "young" and "old" in 1258. The Icefields reconstruction is one of the few millennial long records that infer cooler conditions in 1258. Young trees were defined as trees that were $<$ 50 years old in 1258, while old trees were $>$ 200 years. For the RW data, this resulted in identifying 12 young and 20 old trees, respectively. As MXD

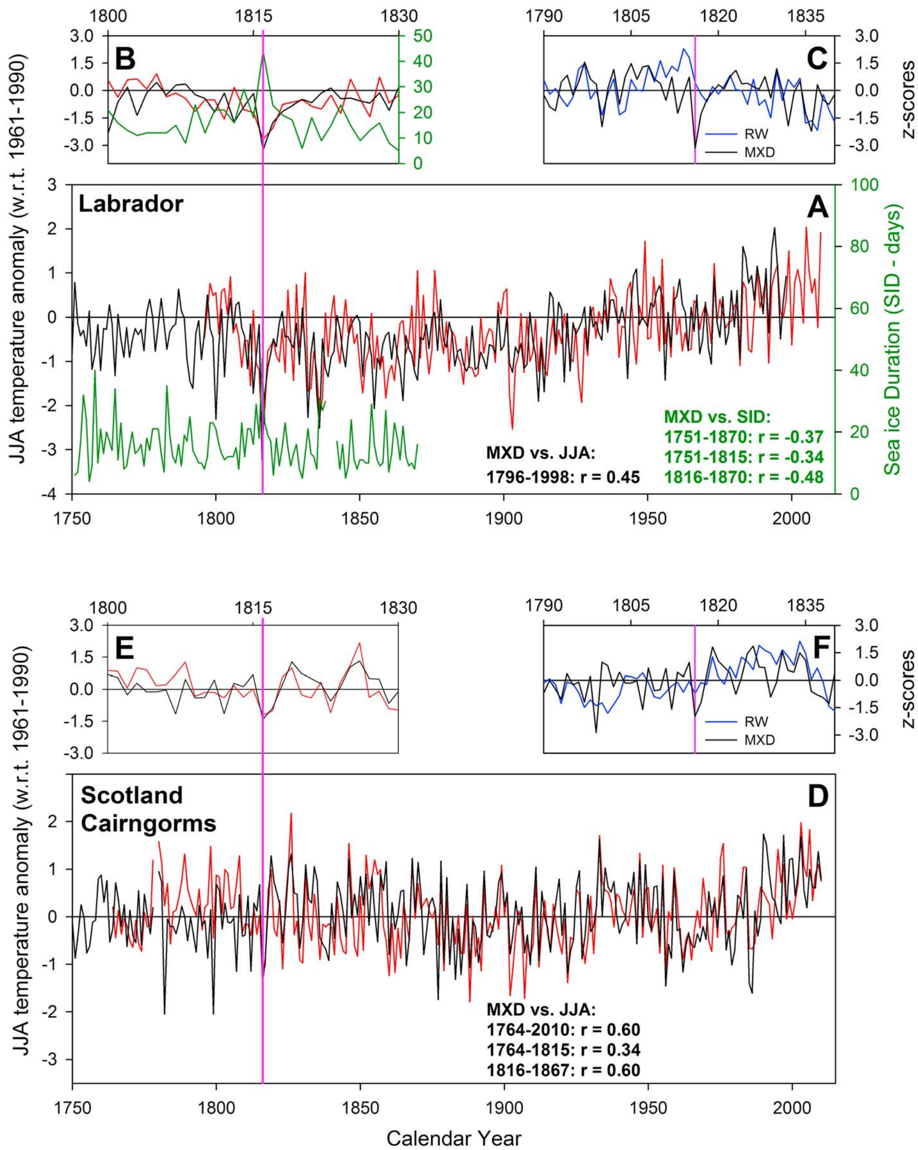

Figure 4. Long instrumental records and MXD/RW series. (a) Labrador MXD (black) scaled to New Haven, CT June–August mean temperatures (red), and the sea ice duration (SID) record (green) for Hudson Bay [*Catchpole and Faurer*, 1985]. For the long instrumental series, the 1850–present data are from the $5 \times 5°$ grid (relevant to proxy data location) CRU land-temperature data set [*Brohan et al.*, 2006] while the pre-1850 period is represented by the long instrumental series of New Haven; (b) As Figure 4a, but only showing the 1800–1830 period; (c) Comparison of the RW and MXD data. Data have been normalized to *z*-scores over the 1790–1840 period; (d) Scottish MXD composite records versus Edinburgh June–August mean temperatures (in red). The MXD raw data were detrended using linear regression functions. For the long instrumental series, the 1867–present data are from the $5 \times 5°$ grid (relevant to proxy data location) CRU land-temperature data set [*Brohan et al.*, 2006] while the pre-1867 period are represented by the long instrumental series from Edinburgh [*Jones and Lister*, 2004]. (e) As Figure 4d, but only showing the 1800–1830 period; (f) Comparison of the RW and MXD data. Data have been normalized to *z*-scores over the 1790–1840 period.

was measured on fewer samples, only 5 and 10 trees were identified for the two age classes. Figure 5 compares the chronologies for both these parameters for both age groups. The lower index value in the MXD data is clear, but the relative deviation for both age classes (34 vs 204 years old in 1258, respectively) is the same. No missing rings were identified in the RW data during crossdating and in fact the 1258 ring, despite its lower density value, has a close to average RW value for the 1220–1300 period. For both parameters, there is no evidence of a missing ring at 1258 when comparing the young and old cohorts—this would be readily identified in the cross-dating process. This suggests that not only is the MFR12a hypothesis, at least for this location, incorrect but again highlights that MXD is the better parameter for examining summer temperature response to volcanic events.

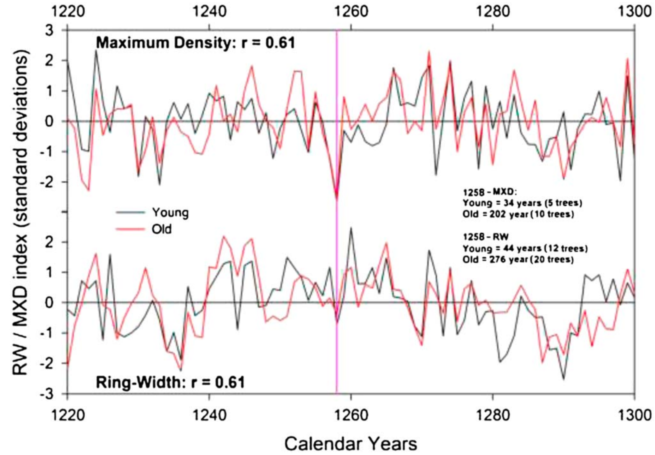

Figure 5. Comparison of time series of MXD and RW around 1258 from young and old trees utilized in the Icefields reconstruction, BC, Canada [*Luckman and Wilson*, 2005]. The tree ring data were detrended using a 200 year cubic smoothing spline and the chronologies normalized to *z*-scores for the period shown (1220–1300). For each parameter, the mean tree age and number of trees are shown for the year 1258 (highlighted with the pink vertical line).

10. Discussion and Conclusions

[28] The tree ring proxies reviewed herein yield distinct but complementary information about the Earth's climate system and its forcings, including volcanically induced cooling over the past millennium. While they all yield information on past temperature conditions, there are distinct nuances between the RW and MXD parameters that must be taken into account before interpreting, and potentially misinterpreting these data. Specifically, it is clear that while RW from at least some species can show volcanic signals on a regional basis [e.g., *Salzer and Hughes*, 2007], using this parameter in hemispheric composites is not likely to be accurate when inferring interannual, quantitative information about past volcanic extremes on a large spatial scale.

[29] As noted above, the RW-based hemispheric reconstructions [e.g., *Esper et al*., 2002; DWJ06], as initially conceived by the dendrochronological community, were never meant to be used to assess hemispheric or global sensitivity on the interannual scale, although they are deemed appropriate for doing so at the lower frequencies, where agreement with model simulations of temperature can be striking (MFR12a). MXD composites have not been as commonly used for this purpose (in part because there are less of them available), but the characteristics of this proxy make it much more appropriate for assessing the sensitivity of the Earth's system to interannual extreme events such as volcanic eruptions [*Briffa et al*., 1998], extant challenges due to the seasonality of response and the spatial variability of climate and the proxy network notwithstanding.

[30] Another important consideration is the issue of divergence, or underestimation of temperatures from tree growth, in such large-scale composites [DWJ06, *D'Arrigo et al*., 2008], although this phenomenon is not ubiquitous by any means [*Wilson et al*., 2007; *Anchukaitis et al*., 2012b; *Esper*, 2012] and appears to be mainly restricted to recent decades and possibly limited to certain species or sites. *Hegerl et al*. [2006] and others have used tree ring-based reconstructions, mostly based on ring width data, but also the *Briffa et al*. [1998] composite MXD, to estimate the sensitivity of the Earth's climate system. One solution might therefore be to create a hybrid of RW and MXD records for such sensitivity estimates. Combined RW-MXD series have been generated that combine the features of both parameters, which would be preferred for attribution studies, but many more MXD long records are needed [*Luckman and Wilson*, 2005].

[31] None of this is to say that there are not challenges associated with using tree ring proxies to identify and evaluate the timing and environmental consequences of volcanic eruptions. As described above, issues related to the seasonality of growth and climate response, the distribution of tree ring sites across the landscape, confounding factors due to biological persistence and autocorrelation, the limited availability of chronologies extending prior to 1300 AD, and potential issues relating to divergence all potentially complicate the process of analyzing the climate signature of volcanic eruptions in the proxy record.

[32] On the other hand, there is no physical evidence (and none has been published) from real tree ring data to support the hypothesis put forward by MFR12a. To the contrary, there is substantial evidence that despite the difficulties discussed herein, independent tree ring data sets show multiple synchronous cooling events consistent with evidence for highly explosive volcanic eruptions, without dating error or dating-induced "smearing" for the past millennium or more. Such "smearing," in MXD composites [e.g., *Briffa et al*., 1998], at least, would be clearly visible if caused by misdating of half or more of the sites included in the large-scale average, as suggested.

[33] Given the past century of the proven methodology of crossdating in dendrochronology, the MFR12a theory can only be validated by using evidence from real tree ring data rather than model simulations (which have been shown to not accurately reflect tree biology or the actual distribution of the DWJ06 network [*Anchukaitis et al*., 2012a]), and specifically tree ring data with a clean high-frequency volcanic signal (specifically, MXD, not RW). Simply altering an

established chronology by adjusting it without justification to find a better match with volcanic events would have no scientific basis. Further, a reasonable familiarity with the biophysical bases of the various tree ring proxies is necessary when interpreting the paleoclimatic record and comparing it to general circulation model simulations. The challenge for those claiming that there are stand-wide missing rings will also be to find locations where there are uniquely severe cold events that are both well documented in instrumental/historical/nontree ring proxies in 1816 and other volcanic episodes, yet entirely absent in any proximal tree ring records. In this regard, we would argue that there is a lesson to be learned here: that a detailed familiarity (including limitations) and mechanistic understanding are essential for evaluating the climate signals of any particular proxy archive [*Jones et al*., 1998; *Frank et al*., 2010].

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