Memory effects in tree-ring width and maximum latewood density in response to volcanic eruptions: evidence from northern Fennoscandia

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Introduction

Large volcanic eruptions, injecting aerosol into the stratosphere, are an important component of the global climate system (Cole-Dai 2010). The aerosols scatter the incoming, shortwave radiation and absorb the outgoing, longwave radiation, thereby warm the lower stratosphere and cool the earth surface (Robock 2000). Estimates of this post-volcanic surface cooling are constrained by the limited number of stratosphere-injecting eruptions during the period of large-scale instrumental measurement (Kelly & Sear 1984, Robock & Mao 1995). This limitation is overcome by using tree-ring based climate reconstructions (Briffa et al. 1998, Cook et al. 2013, Esper et al. 2013a), though the proxy-derived temperature estimates typically explain only a fraction of the variance of surface temperature variability (Frank et al. 2010).

It has recently been suggested (Anchukaitis et al. 2012) to use maximum latewood density (MXD) instead of tree-ring width (TRW) data for assessing the climatic fingerprint of large volcanic eruptions. The rationale for this suggestion is related to potential physiological memory effects inherent to TRW (Cook and Kairiukstis 1990, Fritts 1976) that might blur the signal of distinct cooling or disturbance events and produce temporally extended response patterns (D'Arrigo et al. 2013, Esper et al. 2007, 2010, Krakauer & Randerson 2003). However, the only detailed assessment revealing distinctly differing, parameter-specific, response times to a major volcanic eruption has been presented in Frank et al. (2007a; see their figure 2) indicating a substantially extended TRW decline following the 1815 Tambora eruption, compared to MXD and summer temperature data from the European Alps (see also reviews in D'Arrigo et al. 2013, Anchukaitis et al. 2012). We here evaluate this topic, using the recently developed N-Scan MXD and TRW data from northern Fennoscandia (Esper et al. 2012a), and assess the typical patterns in these tree-ring parameters in response to annually dated volcanic eruptions over the past 750 years.

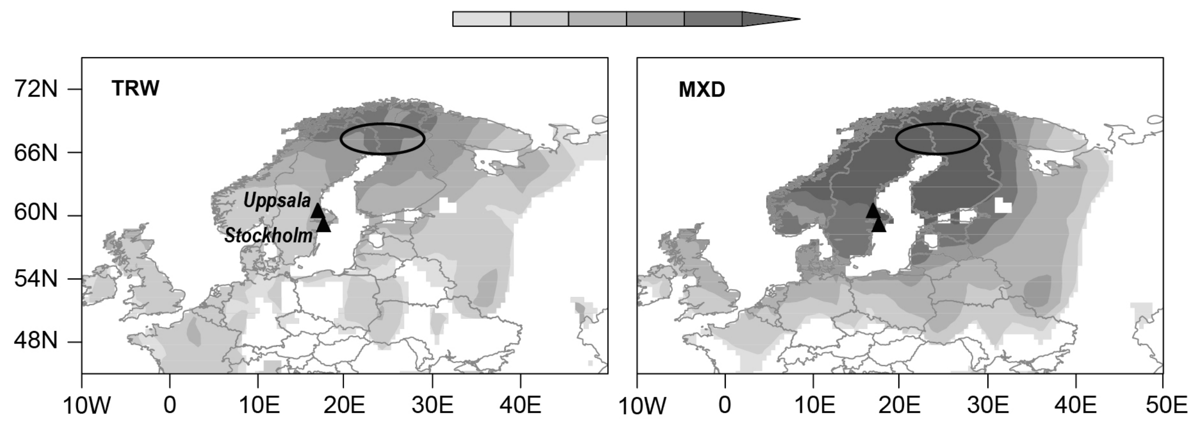

Figure 1: TRW and MXD temperature fields. Location of the N-Scan sampling sites (circle), and spatial correlation patterns of the TRW (left) and MXD data (right) with gridded (0.5° resolution) summer temperatures calculated over the 1901-2006 period. Triangles indicate the location of the long-term temperature stations in Stockholm and Uppsala.

Material and methods

Scots pine data

Five hundred eighty seven TRW and MXD measurement series from lakeshore (Düthorn et al. 2013) and sub-fossil (Eronen et al. 2002) *Pinus sylvestris* L. from northern Finland and Sweden are used in this assessment of potential memory effects. The MXD collection was previously used to reconstruct summer temperatures over the Common Era revealing a millennial scale cooling trend of ~ 0.3°C in northern Fennoscandia due to long-term changes in orbital forcing (Esper et al. 2012b). However, also the TRW data contains a reasonable climate signal explaining ~ 25% of regional summer temperature variance (Fig. 1), making it – in the absence of MXD measurements – a useful paleoclimatic proxy. While the original N-Scan dataset spans more than two millennia, we here only use the past 750 years during which a number of annually dated volcanic events are available.

Age trend removal and chronology building

TRW and MXD data contain entirely different age trends (Fig. 2). While *Pinus sylvestris* MXD measurement series typically increase from ~ 0.5 to ~ 0.7 g/cm^3 during the first two decades of the trees' lifespans, this juvenile trend is followed by a small and fairly gradual decrease of less than 0.1 g/cm^3 up to tree ages > 300 years. In contrast, TRW measurement series are characterized by a steep age trend from ~ 1.2 mm to ~ 0.6 mm over the first eight decades, followed by a still substantial but less severe decrease by another ~ 0.3 mm up to tree ages of 300 years and beyond.

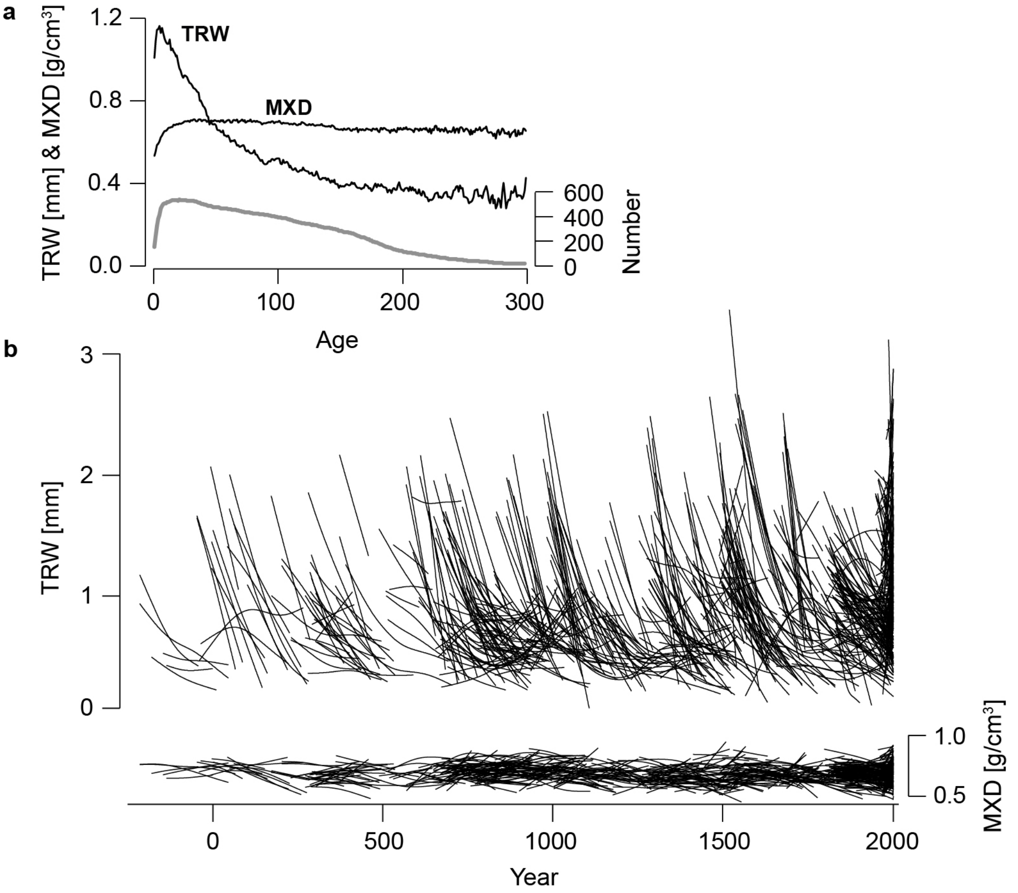

Figure 2: TRW and MXD age trends. ***a****, Arithmetic means of the age-aligned TRW and MXD data shown together with sample replication (bottom panel) declining to 20 measurement series at 300 years.* ***b****, 300-year low-pass filters fitted to the N-Scan TRW (top) and MXD (bottom) measurement series.*

Visualizing these differing age trends over the past two millennia (Fig. 2b) might help emphasizing the much-increased changes that occur when detrending TRW data, compared to MXD. We here applied three approaches (Regional Curve Standardization, RCS; Negative Exponential Standardization, NegExp; and 100-spline Standardization, 100spl) to study the relative contribution of detrending methodology to the estimation of post-volcanic memory effects. In RCS, the regional curve was produced using a 10-year fixed spline, and ratios between the raw measurement series and the regional curve calculated (details in Esper et al. 2003). In the individual series detrendings, we first power transformed the original measurement data (Cook & Peters 1997), and then calculated residuals from NegExp and 100spl functions (Cook & Kairiukstis 1990). No positive slope was allowed in the NegExp detrending to avoid removing long-term increasing trends. In all detrending methods, chronologies were calculated using the arithmetic mean, and variance was stabilized using 300-year splines (Frank et al. 2007b).

Calibration and transfer

The detrended chronologies were calibrated (1876-2006 period) against instrumental June-August (JJA) temperature data recorded at the stations Karasjok, Sodankyla, and Haparanda in northern Fennoscandia. Correlations ranged from 0.43 to 0.53 for TRW, and from 0.72 to 0.77 for MXD, with the RCS detrended chronologies always scoring highest and the 100spl chronologies lowest. The chronologies were transferred into estimates of summer temperature variability by scaling the records (i.e. adjusting the mean and variance; Esper et al. 2005) to the target instrumental data (Fig. 3), and the Expressed Population Signal (EPS) was calculated to estimate the skill of the 100spl detrended chronologies back over the past 750 years (Wigley et al. 1984).

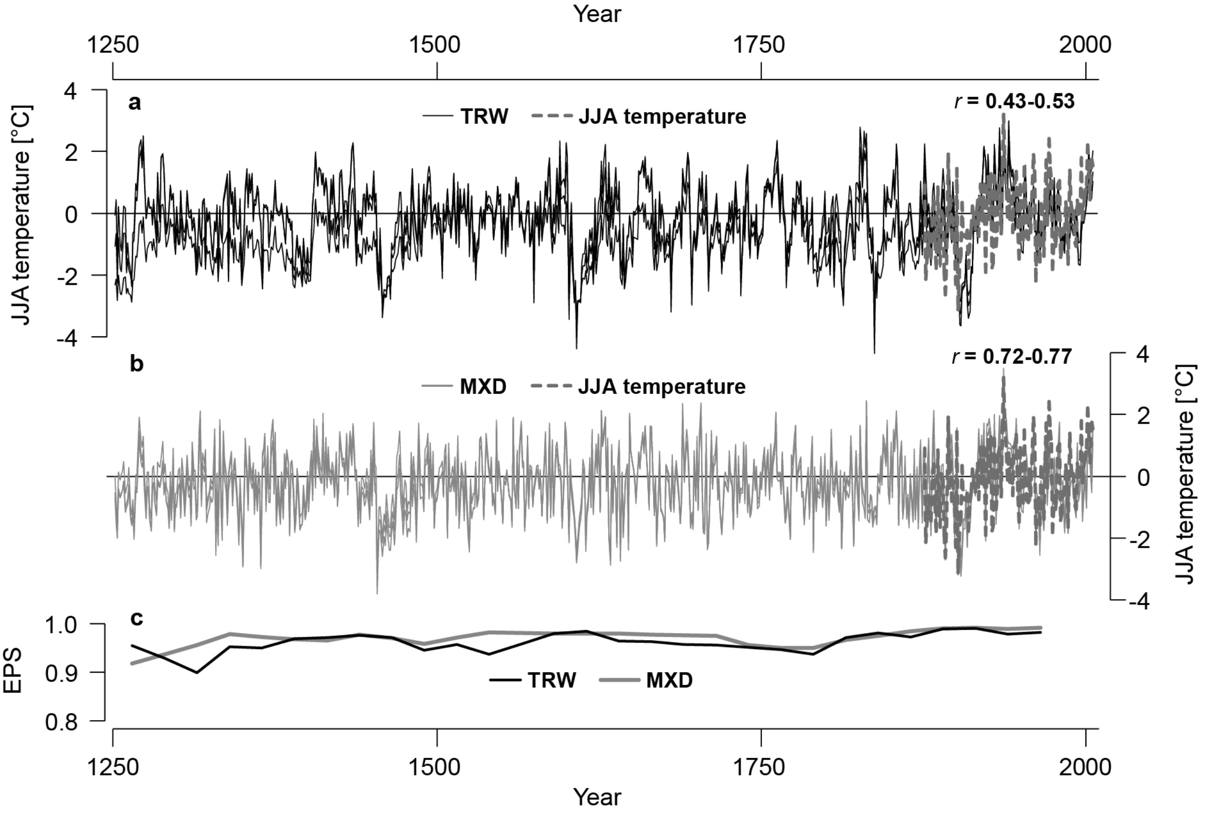

Figure 3: TRW and MXD derived JJA temperature estimates. ***a****, Differently detrended (RCS, NegExp, 100spl) TRW chronologies scaled against regional JJA temperatures (dashed curve) over the 1876-2006 period.* ***b****, Same as in* ***a****, but for the MXD chronologies and JJA temperatures.* ***c****, EPS curves of the 100spl detrended TRW (black) and MXD (grey) chronologies.*

Autocorrelation and SEA

To assess the temporal persistence inherent to the TRW and MXD data, lag-1 to lag-20 autocorrelations of the detrended chronologies, as well as a long instrumental temperature record, were calculated over 1756-2006. The long instrumental record integrates summer temperature readings of the stations in Stockholm and Uppsala in southern Sweden reaching back to the mid 18th century (Moberg & Bergström 1997). While these stations are located towards the southern limit of the proxy correlations fields (particularly for TRW; see Fig. 1) the exceptional length of these data allow an additional assessment of volcanic eruptions fingerprinted in regional temperature data, and comparison with proxy evidence.

Post-volcanic cooling and persistence in TRW and MXD data were estimated using Superposed Epoch Analysis (SEA; Panofsky & Brier 1958). The method comprises aligning the proxy (and instrumental) data by pre-defined dates of large volcanic eruptions, and assessing the estimated temperature deviations prior and subsequent to these events. The eruptions considered here are derived from Esper et al. (2013b) listing 34 events exceeding a volcanic explosivity index (VEI) of 4 over the 1111-1976 period. Three additional, post-1976 events were added here (St. Helens in 1980, El Chichon in 1982, and Pinatubo in 1991) as the N-Scan data reach into the 21st century. We also ran a second SEA including only the ten VEI ≥ 5 events since 1756 that caused substantial cooling (> -0.5°C) in the long Stockholm/Uppsala temperature record, and used these for an additional comparison of observed with TRW- and MXD-estimated cooling patterns.

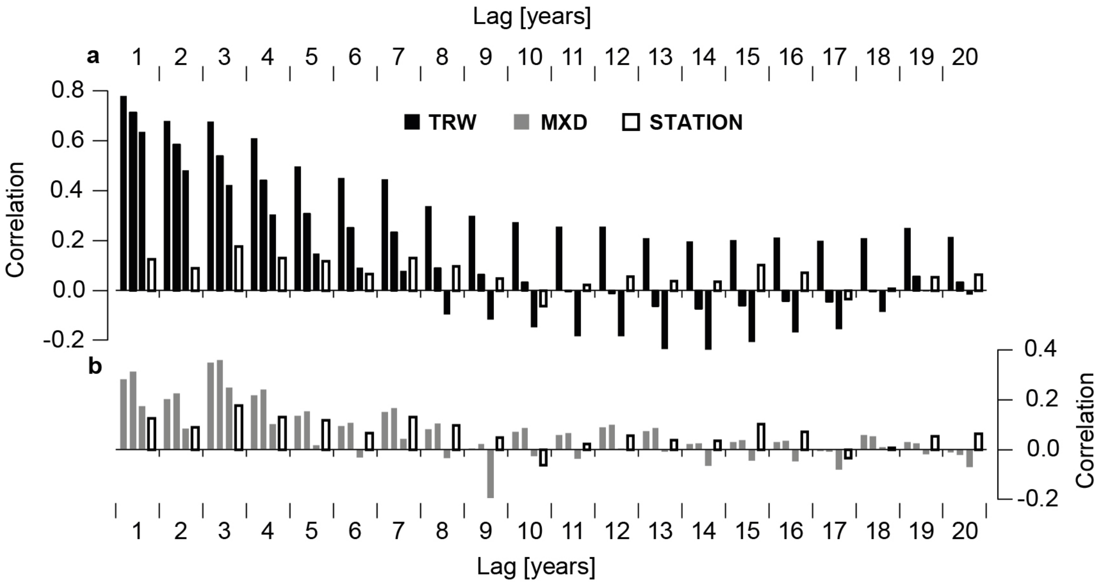

Figure 4: TRW, MXD, and station data autocorrelations. ***a****, Lag-1 to lag-20 autocorrelations of the differently detrended N-Scan TRW chronologies (black bars: left = RCS, middle = NegExp, right = 100spl), and the combined Stockholm/Uppsala summer temperature station data over the 1756-2006 period.* ***b****, Same as in* ***a****, but for MXD and the station data.*

Results

The detrended TRW chronologies contain much more autocorrelation than the MXD chronologies (Fig. 4). TRW chronology lag-1 autocorrelations range from 0.78 in the RCS to 0.64 in the 100spl detrended timeseries. Autocorrelations also decline faster with increasing lag in the 100spl chronology, approaching zero at lag-7, whereas the RCS chronology is characterized by positive autocorrelations up to lag-20. In contrast, the MXD chronologies only contain autocorrelations ranging from 0.31 (NegExp) to 0.17 (100spl) at lag-1. MXD autocorrelations shrink at lag-5, and subsequently fluctuate around zero up to lag-20. Interestingly, the long summer temperature data recorded at Stockholm/Uppsala contain properties similar to the MXD data, including positive autocorrelations ranging from 0.09 to 0.18 up to lag-5, and subsequently minor deviations around zero up to lag-20. Similar to the MXD data, the observational record contains much less memory compared to the TRW timeseries.

The SEA considering 37 annually dated VEI ≥ 5 volcanic events over the past 750 years (Fig. 5a) reveals substantial differences in the response structure of the N-Scan TRW and MXD chronologies. While both parameters indicate strongest post-volcanic cooling at year T+2, in line with evidence from other MXD sites in Scandinavia (Esper et al. 2013b), the MXD data fluctuates back to > 0°C at year T+4, whereas the TRW chronologies continue showing below zero temperature anomalies for another 3-4 years. The 100spl detrended TRW data (the lowest of the three black curves in Fig. 5a) indicates negative values up to T+7 and bounces back to positive temperature anomalies at T+8.

This delayed response pattern in TRW is supported by the SEA applied to only the most significant volcanic eruptions of the past 250 years, during which also long instrumental station data are available (Fig. 5b). In this assessment, average cooling at year T+2 reaches -1.11°C in the instrumental JJA data, a finding in line with the cooling estimated by the MXD chronologies (-1.04 to -1.26°C at T+2). The TRW chronologies show less cooling at T+2, ranging from -0.37°C (RCS) to -0.76°C (100spl). However, while both the station and MXD data bounce back to positive temperatures at T+3, the TRW chronologies indicate below average temperatures up to T+6. This latter feature is evident in all three, differently detrended TRW chronologies.

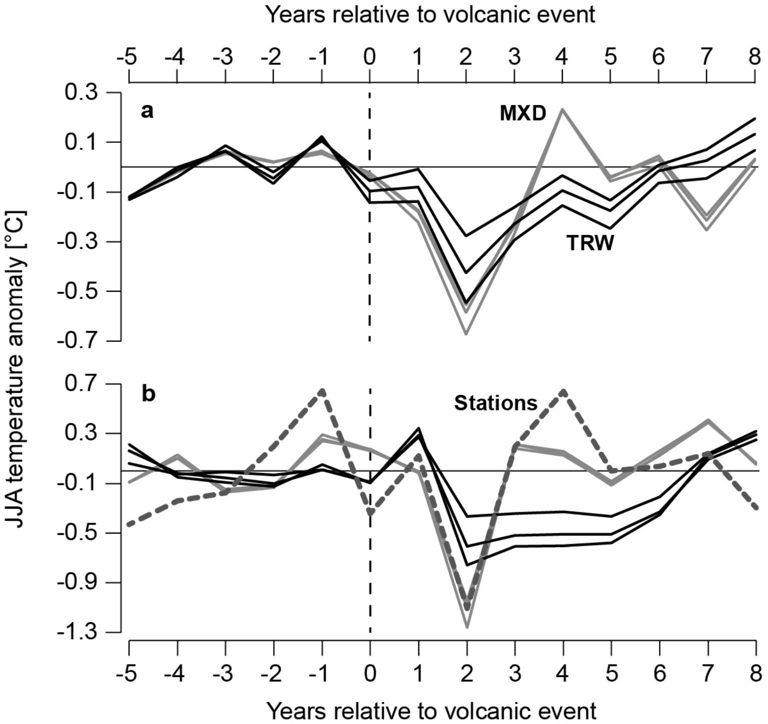

Figure 5: SEA of the TRW, MXD, and long instrumental station data. ***a***, *Summer temperature estimates derived from differently detrended TRW (black) and MXD (grey) chronologies during five years prior and eight years after 37 annually dated VEI ≥ 5 volcanic eruptions since AD 1250 in the Northern Hemisphere and Tropics. For a complete list of volcanic events, see Esper et al. (2013b).* ***b***, *Same as in* ***a***, *but for the 10 volcanic eruptions coinciding with a > -0.5°C summer temperature drop at year T+2 in the Stockholm/Uppsala station record since AD 1756. Station data results are shown with a dashed curve.*

Discussion

Studying the effects of large volcanic eruptions on regional climate is a key objective in dendroclimatology. The development of long, tree-ring based temperature reconstructions enables aligning greater numbers of volcanic events from periods prior to large-scale temperature observations, and thereby reducing uncertainties in post-volcanic cooling estimates (Briffa et al. 1998, Cook et al. 2013, D'Arrigo et al. 2013, Esper et al. 2013a). The analysis of temporal persistence in northern Fennoscandian *Pinus sylvestris* chronologies presented here, revealed substantially larger autocorrelations (up to 0.77 at lag-1) and prolonged post-volcanic cooling (up to 6 years) in TRW data, compared to MXD. The pine MXD chronologies match the autocorrelation structure and post-volcanic cooling pattern retained in the instrumental temperatures recorded since 1756 in southern Sweden. Both the MXD and instrumental data revealed post-volcanic cooling persisted over 2-3 years following large, stratosphere-injecting eruptions. The TRW chronologies, on the other hand, indicated this post-volcanic cooling lasted for another 3-4 years, a finding that is rather related to biological memory effects than actual cooling.

Needle longevity (~ 3-7 years in case of the northern Fennoscandia pines), and storage of starch and protein in parenchyma cells, from previous-year vegetation periods, are likely the key drivers of the increased persistence inherent to the TRW chronologies. Yet the post-volcanic cooling estimates derived from MXD appear to be unaffected by these biological constraints, supporting suggestions to consider this tree-ring parameter for studying the impact of large eruptions on the climate system (Anchukaitis et al. 2012, Briffa et al. 1998, D'Arrigo et al. 2013, Esper et al. 2013b). These findings are in line with evidence from the European Alps indicating a prolonged cooling (by ~ 6 years) in regional TRW data of four conifer species following the VEI 7 Tambora eruption in 1815 (Frank et al. 2007a). Alpine MXD and instrumental temperature data again indicated that the post-Tambora cooling lasted only 1 year.

The Fennoscandian *Pinus sylvestris* TRW data contain a weaker climate signal, compared to MXD, though still pick up post-volcanic cooling centered at T+2 as revealed in both the instrumental and MXD timeseries. The increased memory in TRW chronologies has been considered in some paleoclimatic reconstructions by adjusting the proxy persistence and matching the memory inherent to target instrumental data (e.g., Cook et al. 2002). Among the pine TRW chronologies studied here, we found greatest autocorrelations in the RCS detrended data, compared to the NegExp and 100spl detrendings. The increased memory in the RCS TRW chronology is likely related to the composite detrending approach, in which each measurement series is compared with the mean of all series (Esper et al. 2003). Interestingly, this increased persistence is not translating into an extended post-volcanic cooling, which is most prolonged (up to 6 years) in the 100spl detrended, rather than the RCS detrended, TRW chronology. Explanation of this feature requires further tests including different detrendings applied to MXD and TRW data as well as consideration of additional sites and species.

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