Tree rings and volcanic cooling

To the Editor — In their Letter, Mann and colleagues[1] claim to have identified a discrepancy between the degree of volcanic cooling in climate model simulations and the analogous cooling indicated in a tree-ring-based Northern Hemisphere temperature reconstruction[2], and attribute it to a putative temporary cessation of tree growth at some sites near the temperature limit for growth. They argue that this growth cessation would lead to missing rings in cool years, thus resulting in underestimation of cooling in the tree-ring record. This suggestion implies that periods of volcanic cooling could result in widespread chronological errors in tree-ring-based temperature reconstructions[1,3]. Mann and colleagues base their conclusions solely on the evidence of a tree-ring-growth model.

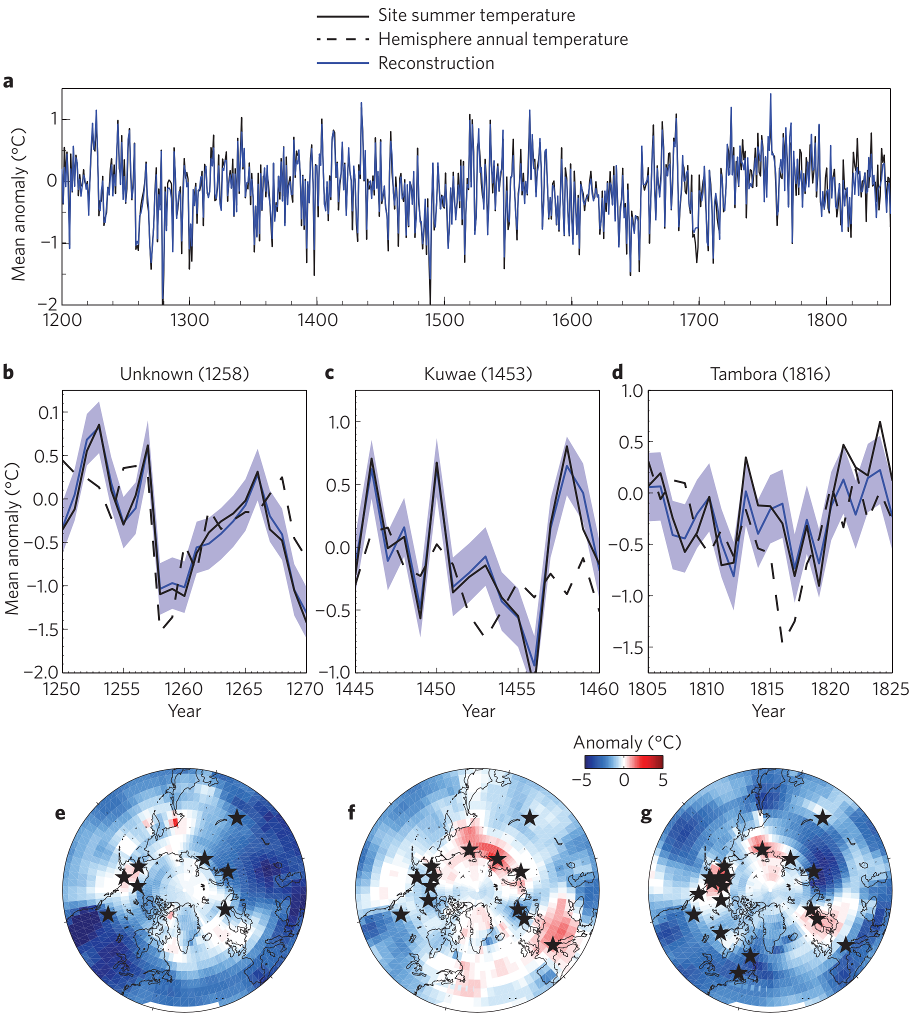

Figure 1 | Simulated response of tree-ring growth to Northern Hemisphere temperature. We used a forward growth model[5] to create a pseudoproxy network for climate variations over the past 800 years (**a**), and show it agrees well with the simulated summer temperatures, even over specific volcanic intervals (**b–d**) highlighted by Mann *et al.*[1] The distribution of sites[2] (shown by stars in **e–g**) and the pattern of temperature anomalies[13] together determine the reconstruction for those years (**e–g**). For comparison with Mann *et al.*[1], the dashed black line shows the CSM1.4 complete Northern Hemisphere annual mean temperature anomaly. Blue shading indicates uncertainty around the reconstruction based on the reduction of error statistic. See Supplementary Information for additional methods.

Here we point to several factors that challenge this hypothesis of missing tree rings; specifically, we highlight problems in their implementation of the tree-ring model used[1], a lack of consideration of uncertainty in the amplitude and spatial pattern of volcanic forcing and associated climate responses, and a lack of any empirical evidence for misdating of tree-ring chronologies.

Several aspects of their tree-ring-growth simulations are erroneous. First, they use an algorithm that has not been tested for its ability to reflect actual observations (Supplementary Fig. 1), even though established growth models, such as the Vaganov–Shashkin model[4,5], are available. They rely on a minimum growth temperature threshold of 10 °C that is incompatible with real-world observations. This condition is rarely met in regions near the limit of tree growth, where ring formation demonstrably occurs well below this temperature: there is abundant empirical evidence that the temperature limit for tree-ring formation is around 5 °C (refs 6,7). Mann and colleagues arbitrarily and without justification require 26 days with temperatures above their unrealistic threshold for ring formation. Their resulting growing season becomes unusually short, at 50–60 days rather than the more commonly observed 70–137 days[4,7]. Furthermore, they use a quadratic function to describe growth that has no basis in observation or theory, and they ignore any daylength and moisture constraints on growth. These assumptions all bias Mann and colleagues' tree-growth model results[1] towards erroneously producing missing tree rings.

Reconstructing simulated temperatures in the same manner as Mann and colleagues, but using a well-tested tree-ring growth model[5] and realistic parameters provides no support for their hypothesis (Fig. 1). Instead we find good agreement between summertime temperatures reconstructed from pseudoproxies and those simulated with a climate model (CSM1.4)[8] (Fig. 1a), for the whole record as well as in specific years following major volcanic eruptions (Fig. 1b–d). Mann and colleagues' principal result arises from their failure to select a realistic minimum temperature for growth, use actual tree-ring chronology locations and recognize that the simulated climate response to eruptions varies geographically (Fig. 1e–g).

Furthermore, the timing and magnitude of cooling in climate model simulations is uncertain. Simulations of the AD 1258 /1259 eruption with an Earth system model[9] place estimates of the maximum Northern Hemisphere summer cooling between 0.6 and 2 °C. This range exceeds the uncertainty range used in Mann and colleagues' comparison with tree-ring reconstructions, and would be even wider if additional error sources (for example, the size distribution of volcanic particulates, the location of the volcano and the season of eruption) were taken into account[10]. An alternative hypothesis of an overestimation of volcanically induced cooling in the simulations cannot be ruled out.

The ring-width-based temperature reconstruction for the Northern Hemisphere[2] does show muted cooling coincident with volcanic eruptions (Supplementary Fig. 2). This response, in part, is related to the spatial distribution of the observing network and to the lagged effects of prior-year weather on subsequent ring formation[11]. An independently produced circum-boreal tree-ring network of 383 maximum latewood density chronologies — a parameter measured from samples cross-dated using ring-width data, and one that is more immediately responsive to abrupt summer temperature changes[12] — shows precise correspondence with the timing of explosive volcanic eruptions (Supplementary Fig. 2). There is no evidence whatsoever of chronological errors or 'smearing' back to 1400, nor do Mann and colleagues present any. On the contrary, there is substantial evidence that independent boreal tree-ring data sets show multiple synchronous cooling events consistent with evidence of highly explosive volcanic eruptions, without significant chronological error, for the past two millennia[13–15].

Limitations in the spatial coverage of trees, insufficient nineteenth-century instrumental data for tree-ring calibration, differences in reconstruction methodologies, and the seasonality of tree growth can cause uncertainties in large-scale dendroclimatic temperature reconstructions, and hence in the quantification of the climatic consequences of volcanic eruptions. However, there is clear evidence that actual boreal tree-ring chronologies are correctly dated and show large-scale, synchronous evidence of volcanically induced cooling[14] (Supplementary Fig. 2). Efforts to estimate the sensitivity of the climate system to significant volcanic eruptions will be enhanced by parallel efforts to improve the coverage and interpretation of the palaeo-observational network, and prescribe radiative forcing of past volcanic events more accurately so that simulations of the radiative and dynamical responses of the climate system to external forcing can be improved. ❐

References

1. Mann, M. E., Fuentes, J. D. & Rutherford, S. *Nature Geosci.* **5,** 202–205 (2012).
2. D'Arrigo, R., Wilson, R. & Jacoby, G. *J. Geophys. Res.* **111,** D03103 (2006).
3. Jansen, E. J. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 433–497 (Cambridge Univ. Press, 2007).
4. Vaganov, E. A., Hughes, M. K. & Shashkin, A. V. *Growth Dynamics of Conifer Tree Rings: Images of Past and Future Environments* (Springer, 2006).
5. Tolwinski-Ward, S. E., Evans, M. N., Hughes, M. K. & Anchukaitis, K. J. *Clim. Dynam.* **36,** 2419–2439 (2010).
6. Körner, Ch. *Alpine Treelines* (Springer, 2012).
7. Rossi, S., Deslauriers, A., Anfodillo, T. & Carraro, V. *Oecologia* **152,** 1–12 (2007).
8. Ammann, C. M., Joos, F., Schimel, D. S., Otto-Bliesner, B. L. & Tomas, R. A. *Proc. Natl Acad. Sci. USA* **104,** 3713–3718 (2007).
9. Timmreck, C. *et al. Geophys. Res. Lett.* **36,** L21708 (2009).
10. Toohey, M., Krüger, K., Niemeier, U. & Timmreck, C. *Atmos. Chem. Phys.* **11,** 12351–12367 (2011).
11. Frank, D., Büntgen, U., Böhm, R., Maugeri, M. & Esper, J. *Quat. Sci. Rev.* **26,** 3298–3310 (2007).
12. Briffa, K. R., Jones, P. D., Schweingruber, F. H. & Osborn, T. J. *Nature* **393,** 450–455 (1998).
13. Larsen, L. B. *et al. Geophys. Res. Lett.* **35,** L04708 (2008).
14. Breitenmoser, P. *et al. Palaeogeogr. Palaeoclimatol. Palaeoecol.* **313–314,** 127–139 (2012).
15. Salzer, M. W. & Hughes, M. K. *Quat. Res.* **67,** 57–68 (2007).

Additional information

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Kevin J. Anchukaitis[1,2], Petra Breitenmoser[3], Keith R. Briffa[4], Agata Buchwal[5,6], Ulf Büntgen[3,5], Edward R. Cook[1], Rosanne D. D'Arrigo[1], Jan Esper[7], Michael N. Evans[8], David Frank[3,5], Håkan Grudd[9], Björn E. Gunnarson[9], Malcolm K. Hughes[10], Alexander V. Kirdyanov[11], Christian Körner[12], Paul J. Krusic[9], Brian Luckman[13], Thomas M. Melvin[4], Matthew W. Salzer[10], Alexander V. Shashkin[11], Claudia Timmreck[14], Eugene A. Vaganov[11,15] and Rob J. S. Wilson[1,16]*

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Mann *et al.* reply — In our Letter, we offered a hypothesis to explain the absence of the expected volcanic cooling responses in tree-ring-based reconstructions of past hemispheric temperatures[1]. In their comment on our Letter, Anchukaitis *et al.* critique various aspects of our approach. Although we welcome alternative hypotheses, we note that their comment does not provide a plausible alternative explanation for this vexing problem. And despite their claim, our analysis does not question the validity of large-scale tree-ring-based reconstructions in general — in fact, we show that tree-ring reconstructions effectively capture long-term temperature trends. We have simply called into question the ability of tree-ring width proxies to detect the short-term cooling associated with the largest volcanic eruptions of the past millennium.

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SUPPLEMENTARY INFORMATION
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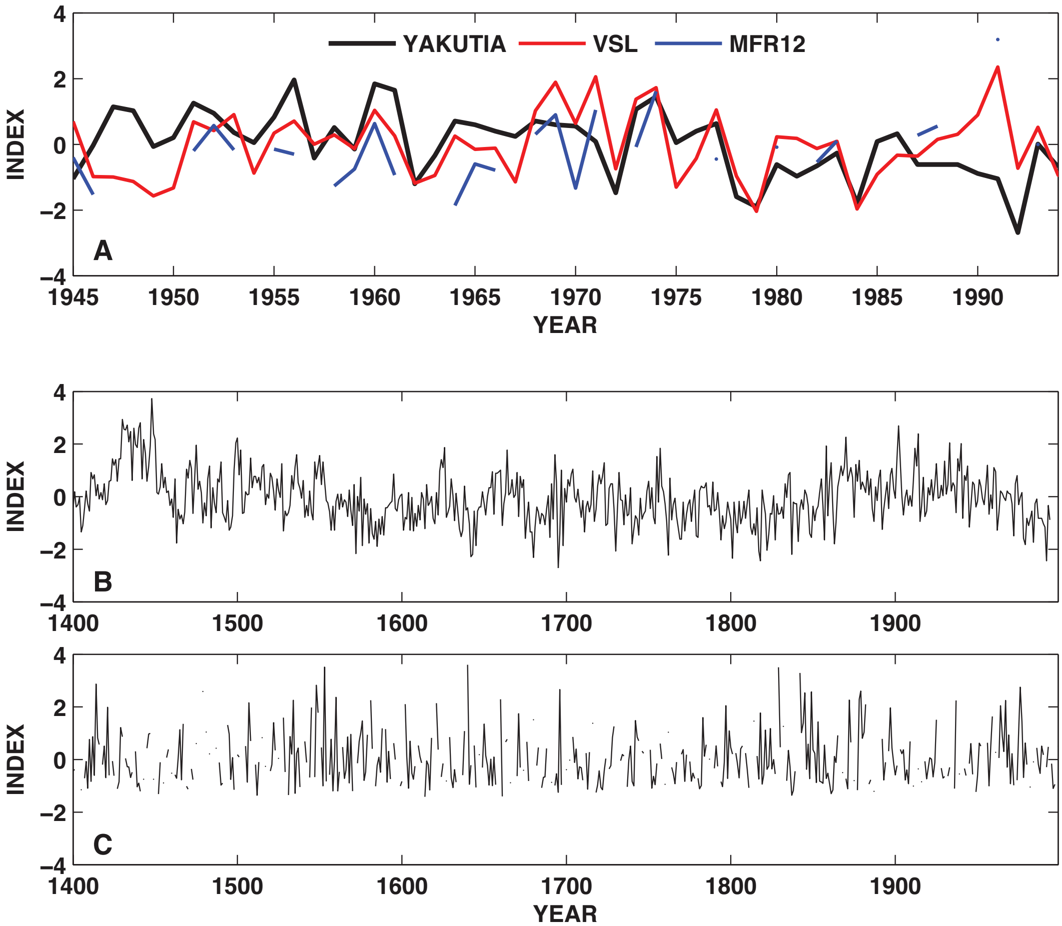

Supplementary Figure S1: Simulations of the DWJ06 Yakutia chronology (70N 146E). We evaluate the skill of the MFR12 algorithm using their default Tmin (10°C) and *nmin* (26 days) parameters using daily data from Chokurdakh, Russia the nearest meteorological station (70N 147E) to attempt to simulate the Yakutia chronology from DWJ06. In panel (A), for these values of Tmin (10°C) and *nmin* (26), MFR12 (blue line) misses 40% of rings for the common overlapping period of 1945 to 1994. However, a simulation with the same data using VSL and the parameter set used in the main body of the manuscript shows good skill reproducing the actual Yakutia ring-width chronology from DWJ06 (black line). The full Yakutia chronology used in DWJ06 is shown in panel (B). For comparison the MFR12 simulated chronology is shown in panel (C), using climate data from CSM1.4, monthly climatology from CRU, and the MFR12 default parameters (Tmin=10C, *nmin*=26). 31% of the simulation years would be considered to not have any ring formation using the MFR12 algorithm and parameter set. Such a feature, if real and undetected, would severely impede skillful calibration, validation, and use of this chronology in climate field reconstructions. Note that the Yakutia chronology has been shown to record growing season temperatures as low as 3.31°C[S7] and the majority of the instrumental calibration period has a growing season temperature below 10°C.

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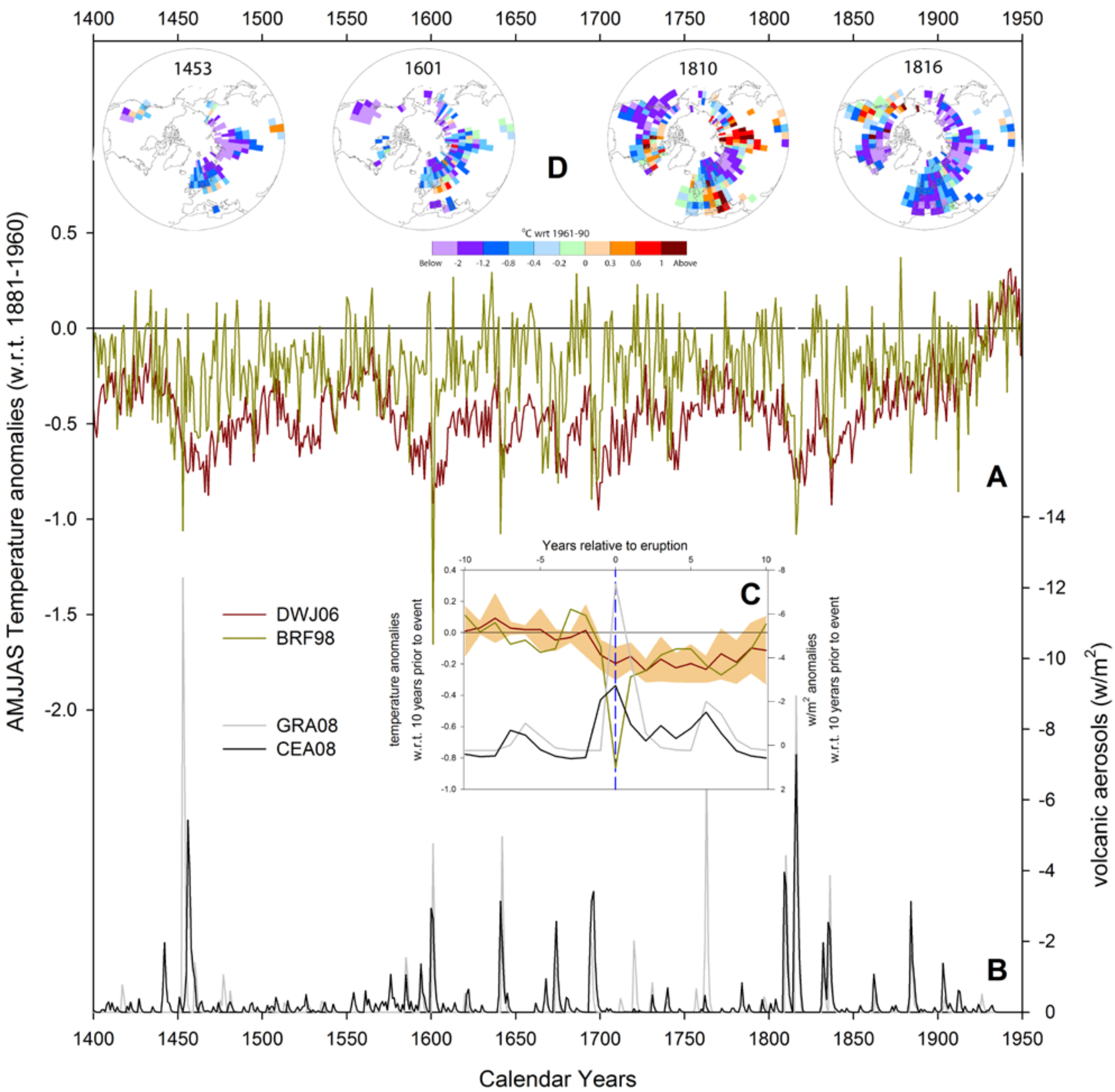

Supplementary Figure S2: A: DWJ06 and BRF98 northern hemisphere reconstructions. Each series has been scaled to extra-tropical (20-90ºN) April-September mean temperatures[S1] over the 1881-1960 period. NB. DWJ06 was originally calibrated to annual temperatures, but the constituent TR records are all summer temperature proxies justifying this re-calibration (see also Wilson et al. 2007[S2]). Spearman's rank correlation between DWJ06 and BRF98 = 0.29 (1400-1994 - $p<0.01$), 0.44 (1400-1452, $p< 0.01$), 0.25 (1454-1599, $p< 0.01$), 0.40 (1602-1805, $p< 0.01$); B: Volcanic aerosol indices (w/m^2) of Gao et al (GRA[S4]) and Crowley et al. (CEA[S5]); C: Superposed epoch analysis of the four events 1453, 1601, 1810 and 1816. Mean values are expressed as anomalies relative to the mean of the 10 values before the event. 2-sigma error is only presented for the DWJ06 data; D: Spatial anomaly maps of reconstructed April-September mean temperature using the BRF98 MXD network[S3].

Supplementary Methods for Figure 1:

Pseudoproxy simulations using VSL[4-5]. Simulations are conducted for each of the actual 19 sites from DWJ06[2], using, as input, the observed annual cycle for each site[1], upon which are superimposed monthly mean temperature anomalies for the corresponding gridpoint from CSM1.4[S6]. Note that the number of sites declines back in time. VSL also requires precipitation anomalies and climatology from CSM1.4 and daylength is calculated based on the latitude of the site[2]. We use a more realistic Tmin=5^{o}C[7]. Uncertainty was calculated as +/- 2 standard error around the reconstruction based on the Reduction of Error (RE) statistic. The raw data and source code to perform our analysis and reproduce our figures can be found here:

Supplementary References

1. Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B. & Jones, P. D. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *J. Geophys. Res.* **111**, 21 PP. (2006).
2. Wilson, R. *et al.* A matter of divergence: Tracking recent warming at hemispheric scales using tree ring data. *J. Geophys. Res.* **112**, 17 PP. (2007).
3. Briffa, K. R. *et al.* Tree-Ring Width and Density Data Around the Northern Hemisphere: Part 2, Spatio-Temporal Variability and Associated Climate Patterns. *The Holocene* **12**, 759–789 (2002).
4. Gao, C., Robock, A. & Ammann, C. Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. J. Geophys. Res. 113, 15 PP. (2008).
5. Crowley, T. J. & Unterman, M. B. Technical details concerning development of a 1200-yr proxy index for global volcanism. Earth System Science Data Discussions 5, 1–28 (2012).
6. Mitchell, T. D. & Jones, P. D. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25, 693– 712 (2005).
7. Hughes, M. K., Vaganov, E. A., Shiyatov, S., Touchan, R. & Funkhouser, G. Twentieth-Century Summer Warmth in Northern Yakutia in a 600-Year Context. The Holocene 9, 629–634 (1999).

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References

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The authors criticize us for not using more elaborate tree-growth models that include other influences such as precipitation. However, the fundamental assumption underlying tree-ring-based temperature reconstructions like those we analysed[2] is that annual growth at temperature-limited treeline locations yields an unbiased estimate of temperature changes exclusively.

Anchukaitis *et al.* criticize our tree-growth parameter choices and, in their Supplementary Fig. 1a suggest that they yield an unrealistic prediction of missing twentieth-century tree rings; however, our analysis[1] predicts no missing tree rings for the twentieth century. We agree that our use of 10 °C as a threshold temperature for growth is at the upper end of the accepted 3–10 °C range[3]. This choice yields the closest fit to the observed tree-ring response, but we see qualitatively similar results for a lower temperature threshold value. Using a simple growing degree-day model with a linear response to temperature (Supplementary Fig. 1), which renders moot their other criticisms of our modelling approach, we show that the underestimation of volcanic cooling by tree rings is substantial for threshold values spanning the entire upper half of the 3–10 °C range, even using a conservative assumption of what constitutes a missing ring, that is, a growing season of less than one week. Including the effect of increased diffuse light[4] caused by volcanic aerosols — an important factor neglected by Anchukaitis *et al.* — leads to slightly better agreement between our growth model and existing tree-ring reconstructions[2]. For growth-model assumptions substantially different from those we adopted, however, the effect produces offsetting and spurious warming responses in the first few years following an eruption (Supplementary Fig. 1)

Anchukaitis *et al.* attempt to reconcile the lack of a cooling response to the AD 1258/1259 in the D'Arrigo *et al.*[2] tree-ring reconstruction with the response predicted by climate models by arguing that the radiative forcing might have been smaller than generally assumed. However, our findings are robust, no matter which of the various published volcanic forcing reconstructions or volcanic scaling assumptions[5] was used. We suggest that the lack of any apparent response to the AD 1258/1259 event in the D'Arrigo *et al.*[2] tree-ring reconstruction is indicative of a fundamental problem. Our analysis provides a plausible explanation for why cooling is observed four years later than expected, and is greatly diminished in magnitude. And it explains a similar discrepancy between the tree-ring reconstruction and the cooling associated with the 1815 Tambora eruption, which is constrained by observational data (R. Rohde *et al.*, manuscript in preparation) that confirm the model-estimated cooling and contradict the muted cooling in the tree-ring reconstruction. The authors of ref. 2 (R. D'Arrigo, personal communication) concede there is a threshold for the cooling recorded by tree-ring growth. Thus, the remaining disagreement appears to be over the extent and larger implications of this effect.

Finally, we must stress that we did not argue, as Anchukaitis *et al.* seem to suggest, that tree-rings are uniformly recording the wrong year of the eruption in a way that can be diagnosed just by looking at composite series (for example, their Supplementary Fig. 2C). Instead, we suggest that sufficiently many individual tree-ring records within the composites are likely to have dating errors (due to potential missing or undetected rings following the largest volcanic eruptions) for the cooling signal to become muted and smeared in the large-scale averages. ❐

References

1. Mann, M. E., Fuentes, J. D. & Rutherford, S. *Nature Geosci.* **5,** 202–205 (2012).
2. D'Arrigo, R., Wilson, R. & Jacoby, G. J. *Geophys. Res* **111,** D03103 (2006).
3. MacDonald, G. M., Kremenetski, K. V. & Beilman, D. W. *Phil. Trans. R. Soc. B* **363,** 2285–2299 (2008).
4. Gu, L. *et al. Science* **299,** 2035–2038 (2003).
5. Crowley, T. J. *Science* **289,** 270–277 (2000).

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience. All code and data used in this comment are available at http://www.meteo.psu.edu/~mann/supplements/TreeVolcano12/Comment/index.html.

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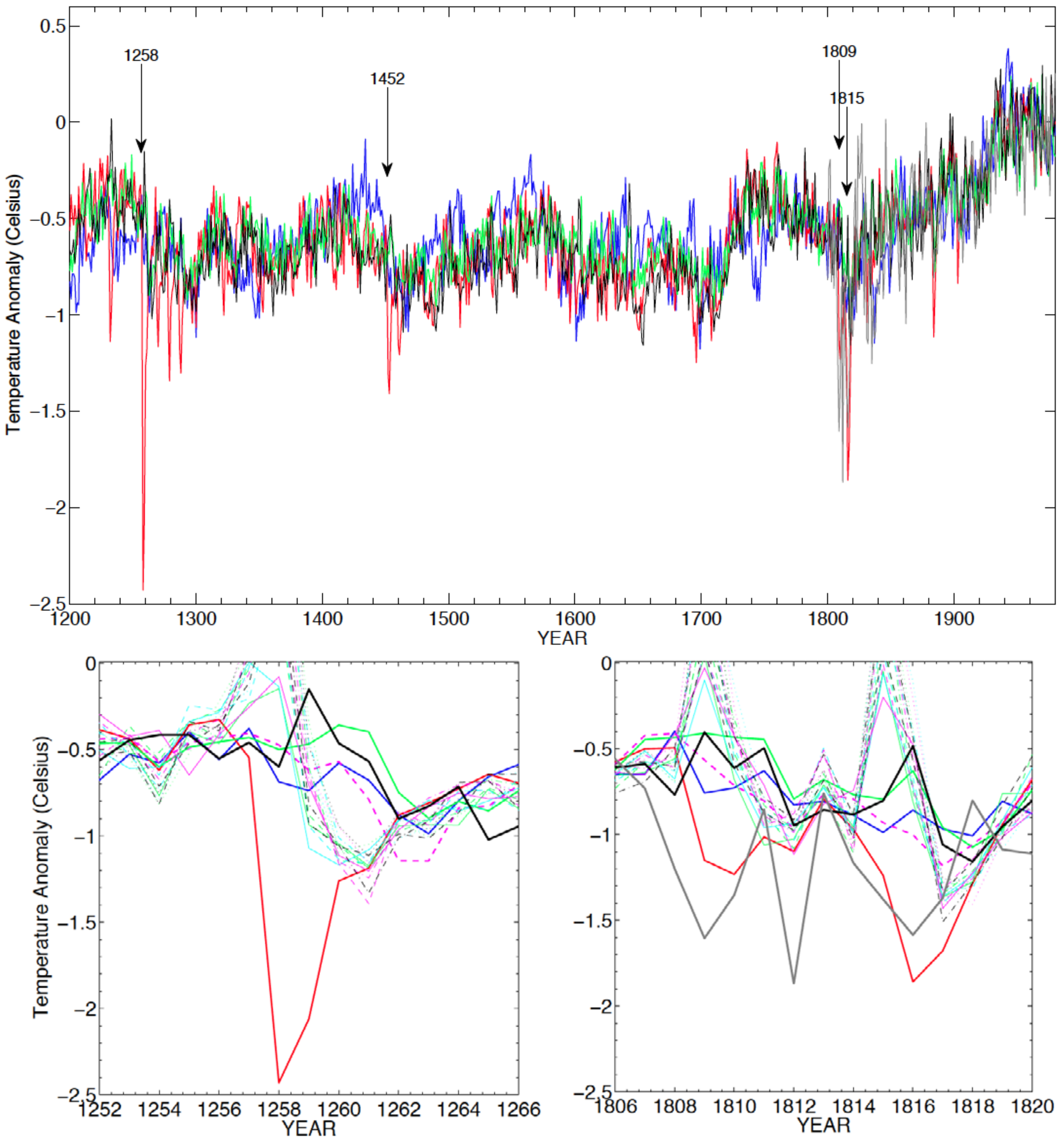

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Figure 1. Comparison of simulated and observed tree-ring reconstructions of NH mean temperature. Conventions are as in Figure 2d of MFR12. Shown are GCM simulation (red), compared with MFR12 GCM-simulated (green) and D06 actual (blue) tree-ring reconstructions. Shown also is GCM-simulated tree-ring series (black) based on simpler tree-growth model formulation used in this comment (with T_{min}=10°C and 26 day threshold for undetectable growth ring), and instrumental global land temperature record back to AD 1800 from "Berkeley Earth Surface Temperature" project (gray). Insets: Expanded views of the response to the AD 1258/1259 and AD 1809+1815 eruptions. Shown also is MFR12 result when the volcanic diffuse-light impact is ignored (dashed magenta) and results using the simpler growth model formulation of this comment for various choices of T_{min} (thin curves: dotted=7°C, dot-dashed = 8°C, dashed=9°C, and solid=10°C), for different thresholds for defining undetectable annual growth ring (green=7 day; cyan=14 day; magenta=21 day, black=26 day). Centering of all series is based on a 1961-1990 modern base period.