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. ❐

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Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience. The Northern Hemisphere tree-ring reconstructions shown in Supplementary Fig. S2 are archived at the National Climate Data Centre: www.ncdc.noaa.gov/paleo/recons.html. The spatial reconstruction plots are available at the University of East Anglia, Climate Research Unit web server: http://www.cru.uea.ac.uk/cru/people/briffa/temmaps/. The raw data and source code to perform our analysis and reproduce our figures can be found at www.ldeo.columbia.edu/~kja/access/volcanic2012.

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Published online: 25 November 2012

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.

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. ❒

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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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Published online: 25 November 2012

Hydroelectric carbon sequestration

To the Editor — The number of hydroelectric dams has increased rapidly in the past two decades and so, too, has the world's interest in their environmental effects[1]. Hydroelectricity is not free from greenhouse gas emissions[2] and, in particular, methane release from dams has been identified as an important contributor to global warming[3]. However, most greenhouse gas assessments neglect the idea that hydroelectric reservoirs are also large carbon sinks and can sequester organic carbon in their sediments[4]. We argue that the common practice of neglecting carbon burial in hydroelectric reservoirs leads to an erroneous characterization of the effect river damming has on the carbon cycle.

Organic carbon in sediments represents carbon dioxide that has been removed from the atmosphere by photosynthesis on land or in water. The fraction of organic carbon that escapes mineralization — that is, the microbial transfer of organic carbon back into carbon dioxide or methane — accumulates and is buried. This process therefore represents a sink for atmospheric carbon. The typically intense inputs of fluvial sediments containing organic carbon and the high trapping efficiency of dams make hydroelectric reservoirs important sites for organic carbon burial[5].

A full assessment of the impact of damming rivers on the carbon budget requires that both carbon burial and emissions before impounding are considered. Burial in a reservoir only represents an effective sink for carbon in cases where, in the absence of the dam, the organic carbon would not have later been buried downstream or in the ocean anyway; or in cases where the buried organic carbon is derived from new production in the reservoir. If these conditions are not met, the burial of land-derived organic carbon