Volcanic induced cooling in instrumental and tree-ring density data

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Introduction

Deciphering the impact of large volcanic eruptions on large-scale climate can yield valuable information on climate sensitivity to radiative perturbations at short timescales (Masson-Delmotte et al. 2013). However, during the era of instrumental climate observations spanning roughly the past 150 years, the number of volcanic events is relatively small, and polar icecores indicate that the amount of radiation-absorbing sulphate injected into the stratosphere was much larger for several eruptions occurring earlier in the last millennium (Gao et al. 2008, Crowley & Unterman 2013). Analysis of climate archives with high temporal resolution, such as tree-rings, can increase the number of detected events and elucidate the full range of possible volcanic impact. Additionally, the large spatial distribution of tree-ring data provides a wide-angle perspective on climate variability that can dampen local anomalies and amplify externally driven climate variability. Thus, a large-scale tree-ring composite can be an appropriate tool for assessing volcanic feedbacks in the climate system.

A good understanding of the relevant proxy/climate-relationship is a prerequisite for analyzing volcanic-induced cooling using proxy reconstructions. Although temperature sensitivity is well established for tree-rings from high latitudes and altitudes (Fritts 1976), and although it is known that especially tree-ring density data are suitable for studying abrupt temperature changes(Esper et al. 2013, 2015), there are a few pitfalls associated with calculatingcooling estimates for volcanic events from tree-ring records:

(i) Usually a linear relationship between temperature and tree-growth is assumed. This can be altered, especially in the case of volcanic events, by the influence of light availability (Robock 2005, Tingley et al. 2014).
(ii) The network of proxy sites can be biased towards regions with weakeror stronger influence of volcanic activity or response to volcanic forcing. While this is a general problem of relatively sparse proxynetworks, it is of particular importance for the evaluationof a climate forcing usingpoint-source data.
(iii) Aggregating or averaging spatial data might reduce the observed amplitude of volcanic cooling.

The hypotheses on light availability referenced in *(i)* are based on large-scale experiments. On local scales, proxy-derived temperatures were found to be in good agreement with long instrumental records (Esper et al. 2013), so that it seems likely that the integration of data over larger regions causes the offset observed in large-scale studies (Tingley et al. 2014). Here we address such potential effects by analyzing a hemispheric composite of maximum latewood density (MXD) chronologies. A summer-temperature reconstruction based on these data reflects distinct cooling in response to the largest eruptions of the last millennium (Schneider et al. 2015). By comparing this dataset with observational data from the 19th and 20th centuries, we intend to test its susceptibility to *(ii)* and *(iii)*, and to verify the cooling estimates derived from this record. We find that spatial aggregation yields systematic underestimation of volcanic induced cooling despite a reasonable hemispheric coverage of the MXDsites.

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Data and methods

The proxy network represents all available MXDchronologies longer than 600 years from the Northern Hemisphere (NH). Data were processed using Regional Curve Standardization (Esper et al. 2003) and scaled (Esper et al. 2005) to local grid-point temperatures in order to derive local temperature reconstructions. The NH average is a 'composite-plus-scaling' (CPS) reconstruction (Von Storch et al. 2006) of extratropical (30-90°N) land-temperatures during the summer months June-August. For details see Schneider et al. (2015).

The instrumental target is the CRUTEM4v-dataset (Jones et al. 2012) with the same spatial (30-90°N, landmass) and seasonal (June-August) coverage. The gridded data reach back to 1850 for many parts of Europe and central North America, but temperature readings do not start before the late 19th or early 20th century for most grid points. In order to provide homogeneous spatial coverage, the NH-mean was calculated after applying a gapfilling procedure via the regularized expectation maximization algorithm using ridge regression (Schneider 2001). At the local scale, this method can introduce significant variance changes at gridpoints with large uncertainty ranges for the infilled data portion. This biasapplied to six sites within the network of 15 sites (see Fig. 1 c and f). Abruptly declining variance in the early portion of these records was adjusted to the level of the late 20th century in order to allow reasonable comparisons on a site-by-site level.

Past climate forcing of volcanic eruptions is usually based on sulphate deposition from multiple ice cores (Masson-Delmotte et al. 2013). Here, proxy and observational data were analyzed for volcanic signals considering the latest global ice core record (Crowley & Unterman 2013). It comprises a reconstruction of stratospheric sulphate expressed in aerosol optical depth (AOD) estimates. We include the volcanic events exceeding an AOD of 0.03 since 1874. Prior to that year the network of observational data is very sparse and the amount of grid points with data available is below 25%. The analysis period ends in 1976 representing the last year of the oldest (i.e. first developed) MXDchronology. Accordingly we included 1883 (Krakatau, Indonesia), 1902 (Santa Maria, Guatemala), 1912 (Novarupta, Alaska) and 1963 (Agung, Indonesia) with peaking AODvalues in 1884, 1903, 1912 and 1964. The temporal lag for tropical eruptions is caused by the delayed dispersion of the ash-column towards higher latitudes. Since AODvalues remain at an elevated level for at least one more year, we also consider this subsequent year. Temperature anomalies in response to volcanic activity were calculated with respect to the 5 pre-eruption years and averaged over the four eruptions.

In order to illustrate how the volcanic signal in proxy reconstructions can be affected by data processing, NH temperatures were reconstructed using the observations from the 15 grid boxes closest to the proxysites. This pseudo-reconstruction, free of proxyinduced noise, was rebuilt a 1000 times using alternative proxy networks, each consisting of 5 randomly chosen input records per continent (North America, Europe and Asia).

Results

Averaging summer temperatures during years of peaking stratospheric sulphate injection yields widespread cooling in the NH with a mean of 0.35°C below the 5 pre-eruption years (Fig. 1a and e). Central North America, southern Europe, western and eastern Asia are key cooling regions, whereas northwestern North America, eastern Europe and central Asia either show no significant coolingor they warm slightly. This pattern is replicated by the proxy records with an outstanding cooling response in northwestern Asia. Local gridpoint temperatures suggest a very similar cooling magnitude in line with the proxy data, and although the response in observational data is on average slightly lower, there is no clear evidence for a general over- or underestimation (Fig. 1c and e).

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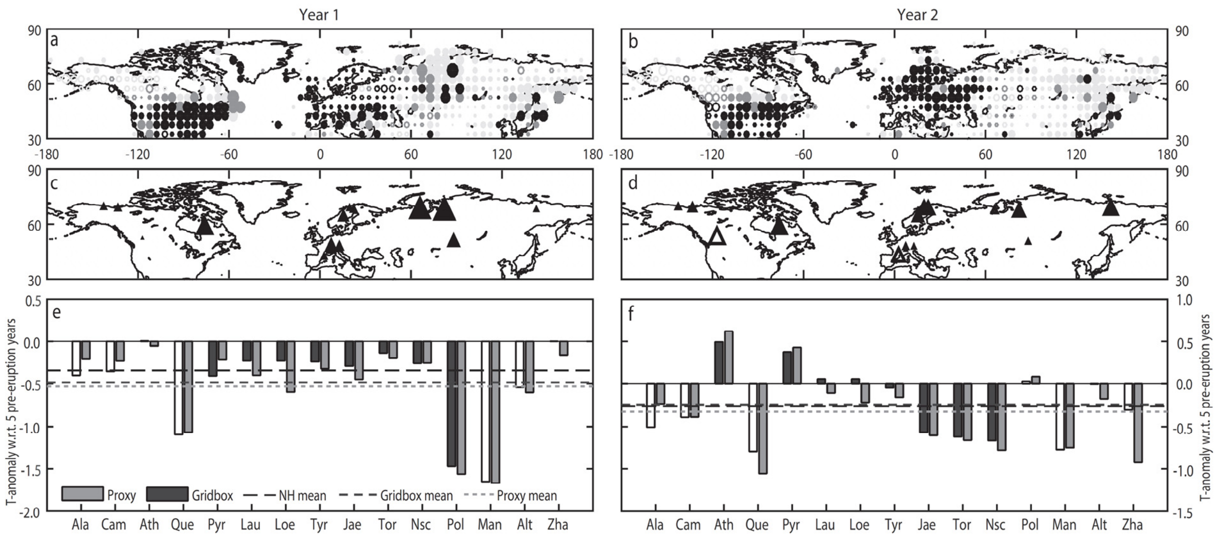

Figure 1: Summer temperature cooling in response to volcanic eruptions in 1884, 1903, 1912 and 1964. (a) Anomalies of gridded summer temperature in years with peaking AOD with respect to the 5 pre-eruption years. Strongest cooling (warming) is indicated with the biggest filled (unfilled) dots. The greyscale represents the number of events covered by a gridbox before gap filling (light grey: 1964, medium grey: 1903, 1912, 1964, dark grey: 1884, 1903, 1912, 1964). (b) As in (a), but for the subsequent year. (c) MXD-sites used for the NH-reconstruction. Lowest (highest) MXD-values in the years with peaking AOD are indicated with the biggest filled (unfilled) triangles. (d) As in (c), but for the subsequent year. (e) Summer temperature anomalies for the 15 MXD sites in years with peaking AOD derived from proxy reconstructions and the gridded temperature field. Unfilled bars indicate gridboxes with short temperature records. A gap filling and variance stabilization were applied. (f) As in (e), but for the subsequent year.

The second year after the sulphate spike is still dominated by cool conditions (-0.25°C on average), but with a clear shift of the key cooling regions (Fig. 1b). The most obvious change is found over Europe, where significant cooling affects the central and northern regions, while southern Europe and western Asia already display warming anomalies. The proxy records again agree with this pattern, and in keeping with the reduced overall cooling, there is more heterogeneity in the local responses: While some sites show even stronger coolingcompared to the first post-volcanic year, others exhibit warming relative to the 5 pre-eruption years (Fig. 1d and f). Averaging the 15 local estimates results in a somewhat stronger cooling than the average of the spatial field over the whole hemisphere. In the first post-volcanic year, reconstructed and observed temperatures are well below the overall average, whereas in the second year only the reconstructed anomalies suggest a slight overestimation (Fig. 1e and f).

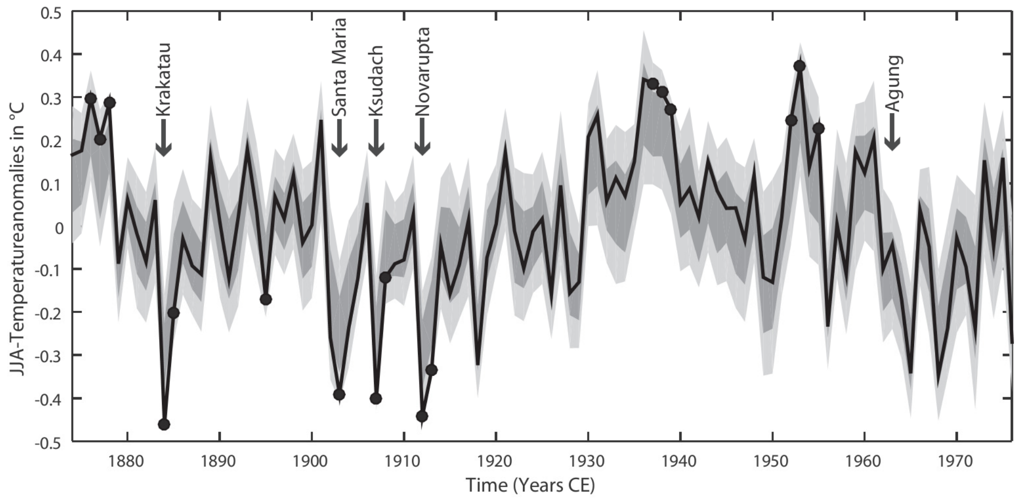

Figure 2 | Summer temperature derived from the average of all grid points (black line) and from 1000 pseudo reconstructions (dark grey: 25th-75th percentile, light grey 10th and 90th percentile). Black dots indicate years in which the NH average exceeds the 25-75 percentile range. Arrows indicate selected volcanic eruptions.

For large-scale examinations, proxy chronologies are compiled into one record, which is then scaled to the NH mean temperature (CPS reconstruction). The NH reconstruction based on the 15 MXD chronologies, representing sites with relatively strong cooling, reveals a considerably reduced response to volcanic forcing compared to the fully-sampled NH mean temperature. Using the reconstructed temperatures as response estimates, the summers were only 0.28°C (0.16°C) cooler in the first (second) year following an eruption. If local gridpoint temperatures for the 15 proxy sites are used as inputs in a pseudo-reconstruction, the observed cooling is similarly weakened: -0.28°C and -0.14°C, respectively for the first and second years.
As these findings contradict the overestimation of cooling found on local scale (Fig. 1e), we recomputed the pseudoreconstruction based on observational data using a randomized site selection scheme. This approach should result in a balanced mix of reconstructions that over- as well as underestimate volcanic cooling with a relatively even distribution around the actual cooling anomaly. The majority of pseudoreconstructions, however, exhibited less volcanic cooling than the overall average (Fig. 2). Even doubling the number of input records to a total of 30 sites does not change this result.

Discussion

Investigating the spatial pattern of summer temperature in response to volcanic eruptions revealed that some regions are not cooling despite massive releases of radiation absorbing sulphate into the stratosphere. The warming in central Asia and western North America is somewhat questionable, however, as data coverage is particularly sparse in these regions and the signal mainly reflects conditions in response to a single eruption (the 1960's eruption of Agung), which caused no clear cooling spike in the NH mean. Some of the observed temperature changes are certainly not significant considering the small number of studied events and uncertainties in the temperature field, i.e. cooling patternsmight change if a larger number of events were included (Esper et al. 2013). Nevertheless, the displacement of cooling in the second year is of particular relevance for a potential bias induced by an uneven spatial distribution of proxy records: While in the current network,average cooling at the 15 proxy-sites was much stronger than the NH average in the first year, the values agreed much better in the second year. This indicates that a proxy network that appropriately represents cooling in the second post-eruption year is not necessarilyaccurate in the first year.

Spatial assembling and processing of the proxy data is an additional source of uncertainty. For the events in 1883, 1902, and 1912, pseudoreconstructions suggest a systematic underestimation of cooling, which is rarely found in years without volcanic forcing. Even the cold anomaly in 1907 (Fig. 2) can be ascribed to a volcanic eruption (Ksudach, Russia). There are also short periods of warmth that are difficult to reproduce with any proxy network. Thisphenomenon, however, cannot be associated with a common driver.

A reason for the underestimation of post-volcanic cooling in sparse proxy networks can be a more spatially homogeneous temperature field when external forcing is active. A reduced percentage of internal variability in such years results in less noise cancellation when calculating large-scale averages and thereby an enhanced temperature peak with respect to long-term variance. For a proxy network of limited spatial coverage, noise cancellation is less effective and, thus, the cooling peak less pronounced. This effect necessarily yields an underestimation of forced temperature changes when interpreting reconstructions based on a proxy network with limited spatial coverage using CPS or linear regression.

Conclusion

Our analysis focused on potential biases in assessing the strength of volcanic forcing using proxy-based temperature reconstructions. At the local scale there is no systematic deviation from the instrumental recordin MXD-based temperature estimates, which is in line with the findings in Esper et al. (2015) who used a different set of volcanic events and similar proxy data. The hemispheric integration, as analyzed herein,revealed that there is no ideal spatial proxy distribution to prevent over- or underestimation of post-volcanic climatic cooling becausethe response pattern changes over time. The proxy network used in this study includes a bias towards regions with stronger cooling in the first year that abatesin the second year. A way to overcome this bias would be to drastically increase the number of predictor chronologies.

By merging data in large-scale reconstructions, it is likely that volcanic cooling is underestimated even if the proxychronologies are a perfect representation of local temperature and of the average NH climatic response. During years of volcanic activity, climate variability is additionally altered by external forcing, probably changing the spatial patterns in the temperature field resulting in different spatial characteristics of temperature anomalies that eventually suppress the volcanic signal in the proxy reconstruction. In contrast to the proxy distribution, this problem is not implicitly resolved using a denser proxy network, but it is possible to estimate the size of the effect by investigating the ratio between peak amplitude and the long-term variance.

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