Timing and duration of post-volcanic Northern Hemisphere cooling revealed from tree-ring records of maximum latewood density

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Introduction

Assessments of large-scale temperature responses to volcanic eruptions are important for improving our understanding of a key natural climate forcing, and more generally for understanding how changes in radiative forcings impact climate feedbacks and modes of variability. Stratospheric aerosols, the main cause of climatic perturbations associated with volcanoes, can vary in origin, size and composition. Their climatic effects may be altered by seasonality and source. Each of these factors determines the degree to which volcanic eruptions have widespread (i.e. hemispheric) impacts on climate (Robock 2000).

Reliable information about the characteristics of volcanic eruptions becomes more limited with increasing time before present. The use of proxy-records allows estimates of volcanic activity and climatic impact before the onset of meteorological observations. The sulphur concentration in ice cores is a common measure to deduce volcanic forcing by translating it into atmospheric sulphate loadings (Gao et al. 2008) or radiation equivalents (Crowley 2000).

The timing and scale of a putative climatic fingerprint is, however, difficult to estimate without using a more direct measure for temperature. Past studies (Briffa et al. 1998a, D'Arrigo et al. 2009) showed that maximum latewood-density (MXD) measurements from tree-rings indeed offer good approximations of the short-term summer cooling associated with volcanic events if the volcanic signal is extracted by averaging over several event years.

This method is nevertheless restricted to the relatively small number of well-dated volcanoes because dating errors reduce magnitude and introduce lag effects in the estimated climatic response (Esper et al. 2013). In fact, monthly dating is required if taking into account the example of a volcanic eruption around the turn of the year. Such a volcano could be assigned to two different calendar years while atmospheric dispersion and timing of the climatic response might be very similar. Ice core dates may also be affected by misdating, particularly those associated with deep-core estimates (Baillie 2008), which is an additional drawback if the most significant events are to be derived from sulphur-records.

To evaluate possible biases that may arise from such dating uncertainties, we here use a compilation of six sulphur-rich monthly dated eruptions that took place during the past millennium for comparison with MXD-based northern hemispheric (NH) summer temperature variability. Events are first analysed on a continental to hemispheric level to evaluate the lag between eruption and maximum cooling. These estimates are then used to adjust the process of averaging over multiple events. The new shape of a typical volcanic cooling pattern is tested for significance using a bootstrap approach.

Data and methods

Northern-hemispheric temperature-reconstructions

A total of 15 MXD site chronologies spanning at least 600 years were used to reconstruct summer-temperature over larger continental regions (Tab. 1). We processed each site separately and applied a power transformation (Cook & Peters 1997) and a Hugershoff detrending (Briffa et al.

1998b) to account for spread-vs.-level relationships and biological age trends. After calculating residuals from the estimated growth curves we built a robust mean for all years with a replication ≥ three series. To remove variance-changes arising from varying replication and signal strength an empirical variance-stabilization (Frank et al. 2007) was applied: we smoothed the absolute deviations from the total mean with a 200-year cubic spline and used the spline function to adjust variance. The chronologies were calibrated against gridded temperature data (Jones et al. 2012) for June-August (JJA) using the closest grid-point (Tab. 1). The common period for the calibration was set to 1926-1987, although two MXD-chronologies drop out in the late 1970s. To retain the full temperature variance a scaling was performed in order to translate tree-ring indices to temperature means (Esper et al. 2005). Since all proxy-records explained a significant amount of local temperature variation (Tab. 1), all site-records were averaged in order to estimate large-scale anomalies. Continental averages were calculated for North America, Europe and Asia using 4, 7 and 4 site-chronologies, respectively. Additionally a simple northern hemispheric average was built as the arithmetic mean of the 3 continental records. Here, we exclusively focus on close-ups for six volcanic events between 1600 and 1883.

Table 1: Tree-ring sites and measures of replication for the 1580-1903 period. The corresponding grid-points refer to the CRUTEM4-dataset, which was used for calibration. The Pearson-correlation between tree-ring data and summer temperature is given as r_{MXD_JJA}.

Site name	***Continent***	***Location***	***Replication Mean***	***Minimum***	***Corresponding grid-point***	r_{MXD_JJA}	***Reference***
Alaska	N-America	68.8N/-142.4E	75	47	67.5N/-132.5E	0.53	Anchukaitis et al. 2013
Altai	Asia	50.2N/90.0E	17	15	52.5N/87.5E	0.62	Myglan et al. 2012
Athabasca	N-America	52.3N/117.3E	28	8	52.5N/-117.5E	0.47	Luckman et al. 1997
Campbell	N-America	68.3N/-133.3E	19	14	67.5N/-132.5E	0.32	Schweingruber, ITRDB
Jaemtland	Europe	63.5N/15.5E	31	14	62.5n/17.5E	0.64	Schweingruber et al. 1988
Lauenen	Europe	46.4N/7.3E	23	11	47.5N/7.5E	0.39	Schweingruber et al. 1988
Lötschental	Europe	47.5N/7.5E	58	44	47.5N/7.5E	0.60	Büntgen et al. 2006
Mangazeja	Asia	66.7N/82.3E	36	3	67.5N/82.5E	0.60	Briffa et al. 2001
Nscan	Europe	67.5N/22.5E	50	29	67.5N/22.5E	0.80	Esper et al. 2012
Polarural	Asia	66.9N/65.6E	30	10	67.5N/67.5E	0.81	Briffa et al. 1995
Pyrenees	Europe	42.5N/2.5E	70	62	42.5N/2.5E	0.40	Büntgen et al. 2008
Quebec	N-America	57.5N/-76.0E	15	7	57.5N/-77.5E	0.69	Schweingruber 2007
Torneträsk	Europe	68.2N/19.7E	26	11	67.5N/17.5E	0.83	Melvin et al. 2013
Tyrol	Europe	47.5N/12.5E	35	16	47.5N/12.5E	0.38	Esper et al. 2007
Zhaschiviersk	Asia	67.5N/142.6E	21	14	66.3N/143.8E	0.27	Briffa et al. 2001

Superposed epoch analysis

A common tool to assess the quantity of volcanic cooling is the superposed epoch analysis (SEA; Panofsky & Brier 1958) that averages temperature patterns after a certain number of events. Including at least 10 years prior and 20 years after the volcanic events allows comparing pre- and post-volcanic time-series characteristics and ensures full coverage of the retention period. Herein all SEAs are displayed as anomalies to the ten pre-volcanic years (lag-10 to lag-1). The year of eruption is referred to as the reference point and located at year zero in the SEA. Since this study focuses on timing and duration of the climatic response, we filtered out the (1) climatically most relevant and (2) well dated volcanic events during the last 800 years - reflecting the original length of the temperature reconstruction.

(1) In a first step an ice-core sulphur record (Gao et al. 2008) was used to identify the most relevant events. The sulphur-record features a global, northern and southern hemispheric

sulphate-loading time-series. The 20 highest peaks were chosen not only from the northern hemispheric record but also from the global one (Tab. 2). Proceeding only with those events that were recorded in both records ensures that high-latitudinal events close to the arctic ice sheet depositions are not misinterpreted. (2) The remaining peaks were compared with a list of monthly dated volcanoes (Siebert et al. 2010). If no major eruption (volcanic explosivity index ≥ 4) was documented in the same year or one year prior, the event was rejected. The others were assigned to a volcano name and region (Tab. 2).

Table 2: Selection of volcanic events over the last 800 years. Only six out of sixteen globally relevant eruptions could be identified as a monthly dated event.

Gao2008		***Month of***	***Volcano name***	***Volcano***
Glo	***NH***	***eruption begin***		***region***
1227	1227	-		
1258	1258	-		
1275	-			
1284	1284	-		
1328	1328	-		
1341	-			
1452	1452	-		
1459	1459	-		
-	1476			
1584	1584	-		
1600	1600	Feb	HUAYNAPUTINA	Perú
1641	1641	Jan	PARKER	Philippines
1693	-			
1719	1719	-		
-	1729			
1783	1783	Jun	GRIMSVÖTN	Iceland
1809	1809	-		
1815	1815	Apr	TAMBORA	Indonesia
1831	1831	-		
1835	1835	Jan	COSIGUINA	Nicaragua
1883	1883	Aug	KRAKATAU	Indonesia
-	1912			
-	1925			
1963	-			

To assess the significance of post-volcanic temperature patterns a bootstrapping technique was employed (Zanchettin et al. 2013). The actual set of six event-years was replaced 1000 times by a set of six randomly chosen years between 1580 and 1903. By calculating SEAs with these random years instead of those containing volcanic events the probability distribution of temperature anomalies can be quantified for each time step. Deviations from the 95 and 99 percentiles of this distributions indicate a significant temperature anomaly.

Results

The two sets of 20 maximum sulphate loadings – global and northern hemisphere – show an overlap of 80% (Tab. 2). Among all 16 common years only six could be assigned to a monthly dated volcano from the record in Siebert et al. (2010). Although the 20 biggest spikes in the sulphur records are evenly distributed over the 800 years of record, all of these six dated events took place in the second half of the millennium. This indicates either incompleteness in the documentary volcano record or dating uncertainties in the ice core records. However, it limits our analyses to the recent half of the record. Despite the 1783 Grimsvötn eruption, the remaining events are of tropical origin, which is fundamental for a widespread and even distribution of volcanic ash over both hemispheres (Budner & Cole-Dai 2003).

The spatial distribution of long-density records is somewhat weighted toward Europe regarding the total number of sites and their individual replication (Tab. 1). On average, European sites also correlate strongest with summer-temperature (r_{ave} = 0.58) for the 62 years of calibration period.

However, sites in North America and Asia also contribute strongly to the amount of explained temperature variance (r_{ave} = 0.51 and 0.57, respectively). While local records are strongly driven by internal climate variability and regional characteristics, these fractions tend to level out if the scale is increased. In hemispheric or continental averages volcanic forcing is unmasked and often leaves a distinct cooling peak (Jones et al. 2003). This is also observed for the climatic effect of the six volcanoes studied herein. While the most negative NH temperature anomalies in the six epochs analysed can be attributed to the volcanic events in five of six cases (either at lag0 or at lag1) the continental records show a number of similarly cold years before or after the actual cooling period (Fig. 1).

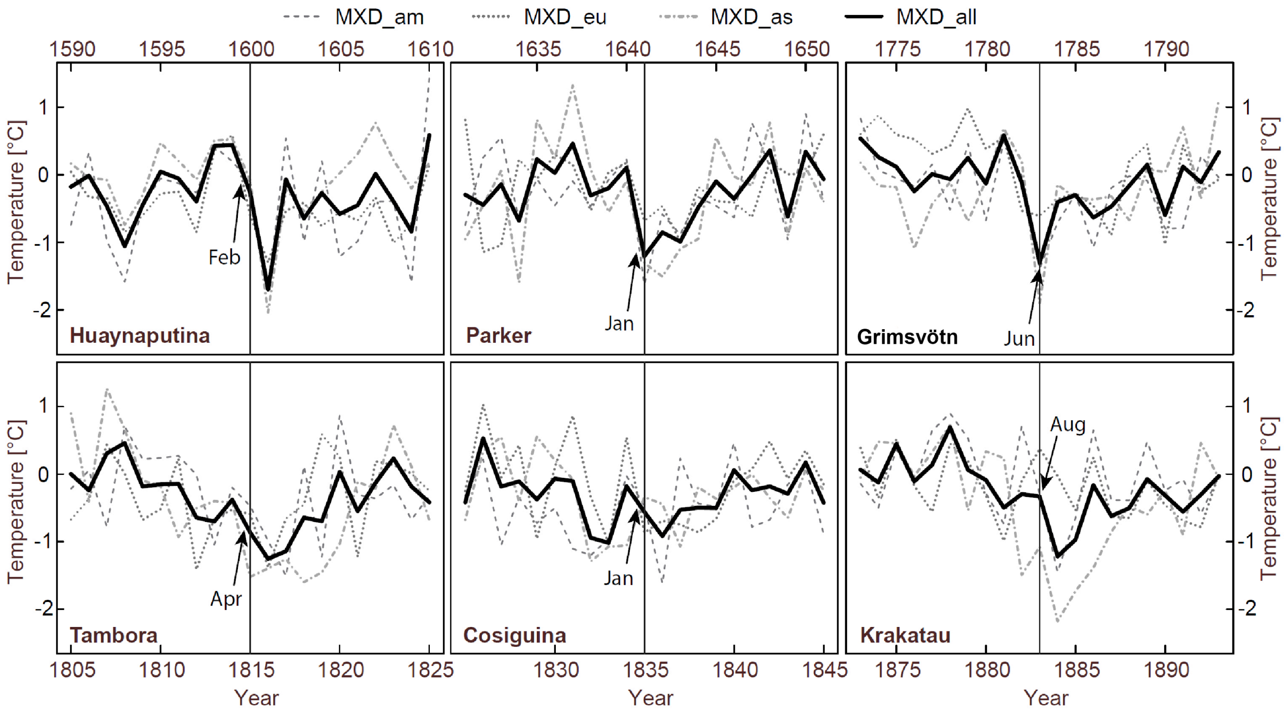

Figure 1: Epochs of strong volcanic events as revealed by continental and hemispheric summer-temperature reconstructions. Temperatures represent anomalies with respect to the 10 years prior to the event. Vertical lines in the middle of each epoch indicate the year of the sulphur-peak in the ice-core records. Arrows give the eruption month as derived from documentary evidence.

Although volcanic cooling is an outstanding feature in these epochs, it varies strongly in timing, magnitude and shape. Temperature decreases mostly abruptly, but is either followed by immediate retention (e.g. after Huaynaputina and Grimsvötn) or it takes two to three years to recover to the original level (e.g. after Mt. Parker, Tambora or Krakatau). The lowest values for hemispheric temperature occur in the year of the sulphur peak or one year later. However, there is no consistent pattern that links this lag to the month of eruption. Eruptions during winter, for instance, can result in a different timing for minimum summer-temperature (Mt. Parker vs. Huaynaputina and Cosiguina). The Grimsvötn eruption in contrast shows maximal summer cooling in 1783 although the ejection of ash does not start before June of the same year. If a mean magnitude is to be derived from these events, such lag-effects result in blurring of the cooling pattern.

To estimate the effect of seasonal transportation patterns and resulting lag-structures, SEAs were calculated in two different ways: (1) For SEA1 the documented years of eruption (which match the years of sulphur peaks) were used as the reference point in the centre of the SEA. (2) In a second approach (SEA2) the reference points were synchronized with the years of minimum post-volcanic summer-temperature in order to estimate the maximum cooling effect. According to Figure 1 these are the years 1601, 1641, 1783, 1816, 1836 and 1884. The resulting SEAs for continental and hemispheric averages show distinct differences in magnitude and timing of post-volcanic cooling

(Fig. 2). After adjusting the reference points the temperature drop is now observed at lag 0 with a rather sharp drop. Only in the European SEAs a clear pattern is missing and cooling is only weakly significant against random fluctuation. The bootstrap-bands are a robust estimate of variance for the SEAs and all values before and after the volcanic spikes stay within the limits of the 99 percentile. The positive effect of averaging regarding the signal-to-noise ratio becomes apparent in a significantly reduced bandwidth for the hemispheric SEAs. The reference period for the calculation of anomalies is also accompanied by a slightly smaller bandwidth, especially for the Asian SEAs.

With respect to the standard error of the mean the most significant cooling is found for the northern hemispheric SEA2 with a temperature difference of 0.93°C between lag -1 and lag 0. This value is smallest for Europe with only 0.44°C.

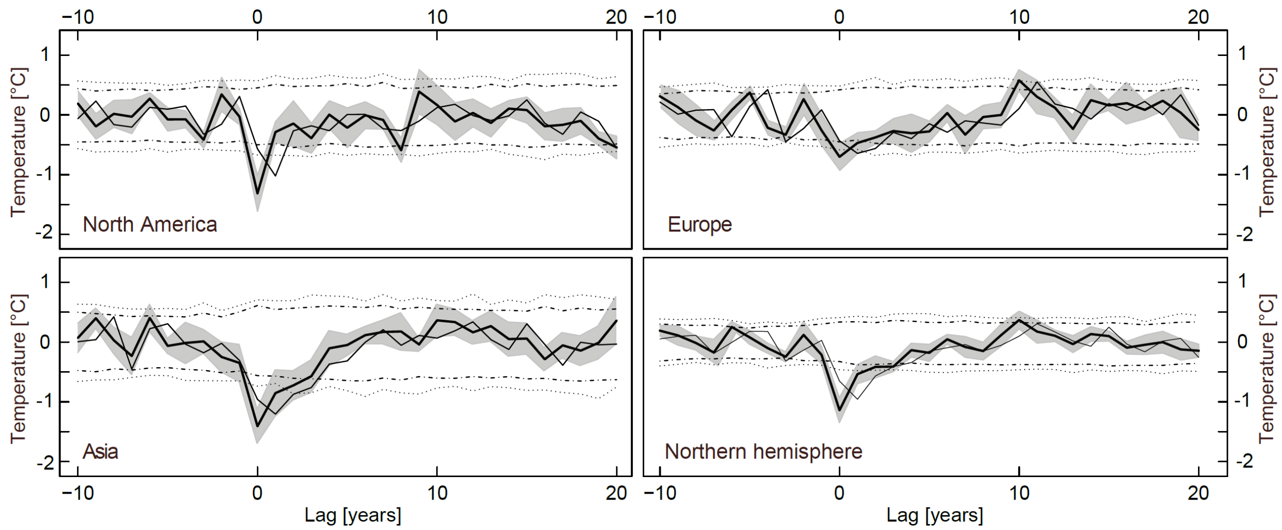

Figure 2: SEAs for different continental averages and the Northern hemisphere. The bold lines represent SEA2 with epochs centred around 1601, 1641, 1783, 1816, 1836 and 1884. SEA1 (thin lines) used the documented/sulphur record years 1600, 1641, 1783, 1815, 1835 and 1883. Temperatures represent anomalies with respect to the 10 years prior to the event. Dashed lines indicate the 95 and 99 percentiles of a bootstrap approach to assess significance. The grey bands show the standard error of the mean (standard deviation divided by the square root of the sample size) for each time-step.

Discussion

This study documents the potential of MXD-data in storing the climatic response to volcanic eruptions, which is an important information regarding the calibration of sulphur-records and climate models. Although the number of events studied herein had to be limited due to methodological reasons we found distinct patterns of post-volcanic cooling with the help of averaged SEAs. At the same time the basic need for a detailed analysis of single events was revealed. Despite the influence of other climate forcing parameters and internal variability the volcanic impact resulted in a cooling in all 6 epochs and allowed for an improved alignment according to the cooling pattern. This alignment had to follow a visual inspection of the single temperature time-series because no robust relationship between the seasonality of the eruption and the offset between eruption and cooling could be established. Climatic responses are observed in the next growing season or in that of the following year. Only the high-latitudinal eruption of Grimsvötn in summer 1783 translates in immediate cooling whereas magnitude and duration of the cooling associated with this event are in line with eruptions of tropical source.

Compared to other studies (Briffa et al. 1998a, D'Arrigo et al. 2009), the observed cooling-response in SEA2 for North America, Asia and the hemisphere is fairly strong in magnitude. To some extent this is caused by the new approach of aligning by the climatic impact, but it is also a corollary of using only the 6 biggest events. While these SEA2s show temperature anomalies of

more than -1°C, the European SEA2 is only weakly significant. This can be attributed to the large portion of alpine records, which respond less to volcanic forcing (Esper et al. 2013).
The two- to three-years temperature depressions in the SEA1s suggest a slow emergence of volcanic cooling with the minimum temperature observed at lag1 after the eruption. In fact, this pattern is an artefact of shifting seasonality, which should be considered in the interpretation. In a larger setup with more volcanoes this approach could, however, help to quantify the number of volcanoes with response at lag0, lag1 or lag2.
According to theoretical sulphur transport (Gao et al. 2008) and observational data of atmospheric optical depth (Crowley et al. 2013) it is more likely to find a sharp temperature decline with a subsequent - possibly fast - recovery. This concept would be better in line with the pattern that was found for the SEA2s and justifies the adjustment of the temperature-minima. Irregular lag-structures, however, limit the potential to upscale this approach by incorporating more monthly dated volcanic events. But using a simple temperature-minimum between lag0 and lag2 as reference point – as in this study – solves the problem although it might introduce a bias in the adjustment procedure if noise or internal variability alter the volcanic signal.

Conclusion

This study presents a data-adaptive way of analysing the volcanic impact on temperature records across the NH. The method suggests results that are considerably different from previous studies concerning both duration and magnitude of post-volcanic cooling. Adding more volcanoes of smaller size will likely mitigate the increased magnitude. The shape of the climatic response shows an abrupt temperature drop and a short recovery period. Since the alignment of volcanic impacts followed a visual inspection, it would be desirable to objectify this step. The high quality and spatial coverage of the underlying database indicate that the detection of cooling patterns can potentially be automated by applying objective detection algorithms (Hendry & Pretis 2013). This would help to expand this method to more advanced climate time-series and an extended set of volcanoes, which would likely result in more significant results.

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