Site-specific temperature response to seven major volcanic eruptions over the last millennium

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Introduction

Volcanic eruptions have major impact on our climate system. Through the injection of aerosols in the atmosphere, incoming solar radiation is scattered, resulting in a cooling of the earth's surface (Robock 2000). Climate model simulations for the past millennium implement ice core based volcanic forcing records (e.g. Crowley & Unterman 2013, Gao et al. 2008) to evaluate the cooling effect of volcanic eruptions (Schmidt et al. 2011). Even though a new ice-core based record was established by Sigl et al. (2015), there are still uncertainties regarding the timing and intensity of volcanic events and the subsequent temperature response. To illuminate discrepancies between volcanic forcing and reconstructed temperatures Schneider et al. (in prep.) established a new volcanic event history over the last millennium by detecting major eruptions in tree-ring derived hemispheric scale temperature reconstructions. However, volcanically induced temperature responses are more pronounced in high compared to mid latitudes (Esper et al. 2015), can also vary on local scale and are dependent on the event itself (Briffa et al. 1998). Knowledge about the spatial effects of specific eruptions is thus important for the implementation of volcanic forcing records into atmospheric circulation models, which simulate past climate but also project future climate conditions.

Here we analyse the site-specific temperature response to seven major volcanic events over the last millennium by using all millennium length temperature reconstructions of the Northern Hemisphere (Fig. 1) and test the dependence of cooling to geographical location.

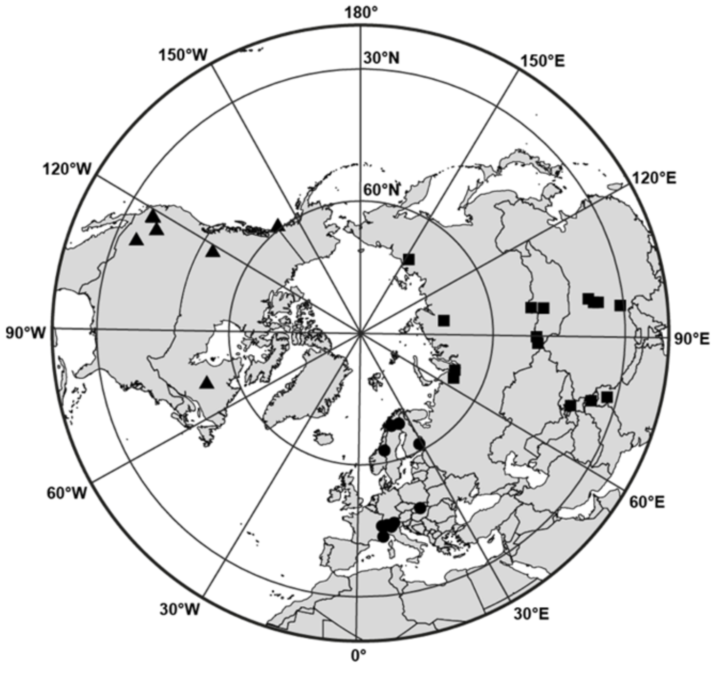

Figure 1: Location of the 36 millennium-length tree-ring based temperature reconstructions used in this study including 13 records in Europe (points), 15 in Asia (squares), and 8 in North America (triangles).

Material and Methods

Tree-ring based temperature reconstructions

We use all 36 existing tree-ring based temperature reconstructions from the Northern Hemisphere reaching back to AD 1000 (see Esper et al. 2016 for details). Thirteen records are located in Europe, 15 in Asia and eight in North America (Fig. 1, Table 1). All these records and the different characteristics of the underlying tree-ring data have been examined in-depth by Esper et al. (2016) (updates at: www.blogs.uni-mainz.de/fb09climatology/reconranking). We herein use only the final temperature reconstructions from the original articles. This millennium-length dataset is a unique network as it enables the investigation of volcanic effects over the whole last millennium.

*Table 1: Millennium-length tree-ring based temperature reconstructions from the Northern Hemisphere. * indicates MXD-based temperature reconstructions.*

Continent	Record	Reference	Lat./Lon.
Europe	Tornetraesk (MXD)*	Melvin et al. 2013	68.2N 19.5E
	Tornetraesk (TRW)	Melvin et al. 2013	68.2N 19.5E
	N-Scan*	Esper et al. 2012	67-69N 20-28E
	Finland	Helama et al. 2010	67-69N 20-28E
	Jämtland	Linderholm & Gunnarson 2005	63.2N 12–13E
	S-Finland*	Helama et al. 2014	61-62N 28-29E
	Tatra	Büntgen et al. 2013	48-49N 19-21E
	Swiss/Austrian Alps	Büntgen et al. 2005	46-47N 7-11E
	Central Alps	Büntgen et al. 2011	46-47N 10-12E
	Lauenen*	Schweingruber et al. 1988	46.4N 7.3E
	Lötschental*	Büntgen et al. 2006	46.3N 7.8E
	Alps (Larch)	Büntgen et al. 2009	45-47N 6-14E
	French Alps	Büntgen et al. 2012	44N 7.3E
Asia	Taimyr	Briffa et al. 2008	70-72N 95-105E
	Indigirka	Sidorova et al. 2006	70N 148E
	Yamal	Briffa et al. 2013	67-68N 69-71E
	Polar Ural*	Briffa et al. 2013	66.8N 65.6E
	Central Asia	Davi et al. 2015	51.1N 99.7E
	Mongun	Myglan et al. 2012a	50.3N 90E
	Dzhelo	Myglan et al. 2012b	50N 87.9E
	Mongolia	D'Arrigo et al. 2001	48.3N 98.9E
	Tien Shan	Esper et al. 2003	40N 71-72E
	Qilian	Zhang et al. 2014	38.7N 99.7E
	Wulan	Zhu et al. 2008	37N 98.7E
	Dulan	Liu et al. 2009	36N 98-99E
	Karakorum	Esper et al. 2002	35-36N 74-75E
	W-Himalaya	Yadav et al. 2011	32-33N 76-77E
	Qamdo	Wang et al. 2014	31.1N 97.2E
N-America	Gulf of Alaska	Wiles et al. 2014	58-61N 134-149W
	E-Canada	Gennaretti et al. 2014	54-55N 70-72W
	Icefield*	Luckman & Wilson 2005	51-53N 117-119W
	Great Basin	Salzer et al. 2014	37-40N 114-118W
	Crabtree	Graumlich 1993	36.5N 118.3W
	Boreal Plateau	Lloyd & Graumlich 1997	36.3N 118.5W
	Upper Wright	Lloyd & Graumlich 1997	36.3N 118.3W
	Southern Colorado	Salzer & Kipfmueller 2005	35.3N 111.7W

Selection of volcanic events

The selection of volcanic events was performed according to the new volcanism reconstruction by Schneider et al. (in prep). This event history is based on a break detection algorithm applied to the three most recent Northern Hemisphere tree-ring based temperature reconstructions: Schneider et al. (2015), Stoffel et al. (2015) and Wilson et al. (2016). The intensity of the detected volcanic events varied among these temperature records but we here choose all events which rank within the top ten of all three records resulting in seven overlapping events: 1109, 1258, 1453, 1601, 1641, 1783 and 1816. All these events can be located to tropical latitudes except of the 1783 Laki (Iceland) eruption. Note that these events indicate the year with the strongest cooling which does not necessarily represent the year of the actual eruption (see Schneider et al. in prep).

Temperature response to volcanic events

We calculated the temperature deviations for each of the above mentioned seven volcanic events with respect to the five pre-event years. This was done for each of the 36 temperature reconstructions separately. We then focus on the event year and the year following. Even though volcanic forcing can cause longer lasting cooling we refrain to consider other post-event years. Tree-ring width (TRW) can feign temporally extended cooling through biological memory effects which is not the case in maximum latewood data (MXD) (D'Arrigo et al. 2013, Esper et al. 2010, 2015); in this study only seven temperature reconstructions are based on MXD data (see Table 1) indicating that the absolute temperatures have to be interpreted with care. We assume, however, that the TRW-records are biased similarly, allowing the investigation of spatial patterns. We applied a linear regression model to test the relationship between temperature response and latitude.

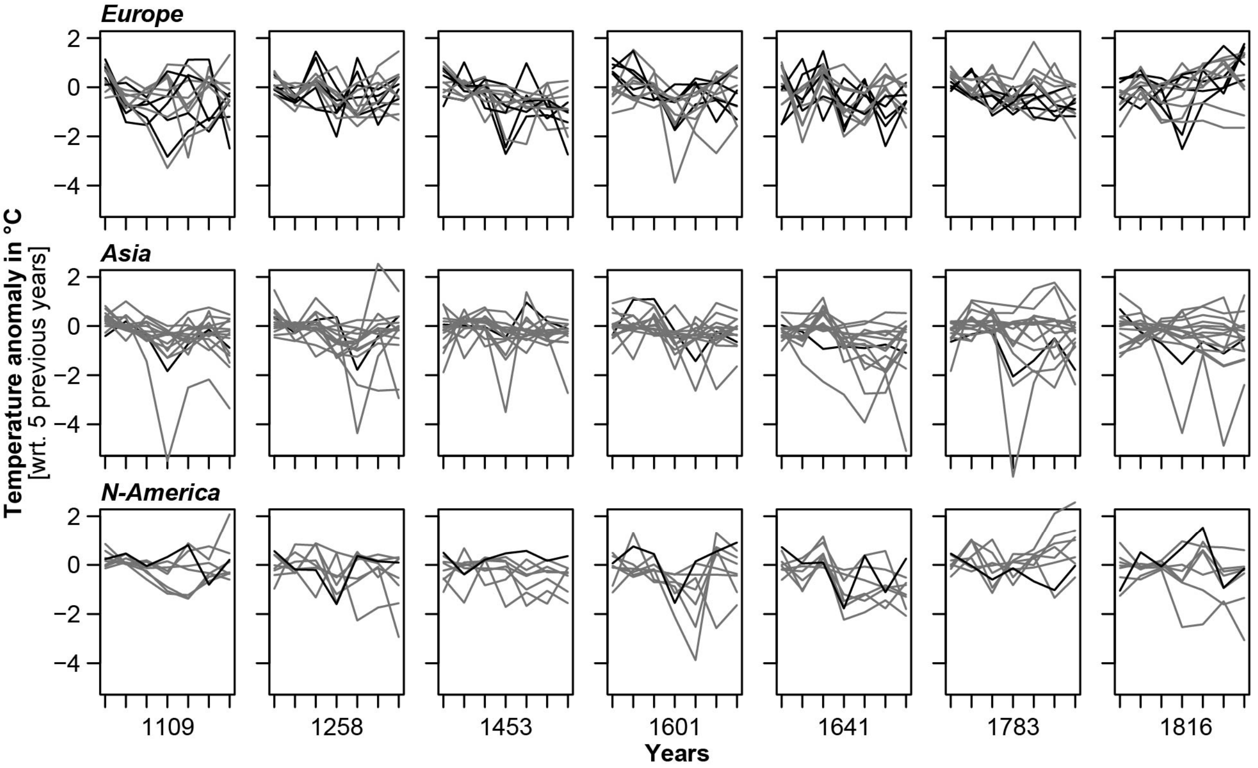

Figure 2: Temperature response in Europe, Asia and North-America to seven major volcanic cooling events. Temperature anomalies are calculated with respect to the 5 pre-event years. Grey lines refer to TRW and black lines to MXD-based temperature reconstructions.

Results and Discussion

Temperature response to volcanic events

The temperature response pattern to specific volcanic events varies considerable within a continent and also among the continents (Fig. 2). Interestingly, not only the TRW-based reconstructions (grey lines in Fig. 2) show a wide spread of temperature responses but also the MXD reconstructions (black lines in Fig. 2) show different responses. We expected a more pronounced and synchronous cooling in the MXD-based reconstructions as MXD contains clearer and less biased signals compared to TRW (D'Arrigo et al. 2013, Esper et al. 2010, 2015). Also, the timing of the maximum cooling differs among the sites. For example, the 1258 event caused cooling almost all-over Europe and North America during the event year, while in Asia maximum cooling occurred in 1259. The magnitude of cooling also strongly varies, the extra-tropical eruption in 1783 for example, caused only little cooling in Europe and North America but is quite pronounced in Asia, meaning that the location of the eruption itself influences the temperature response.

The temperature patterns also differ among the events, indicating that these seven volcanic eruptions caused different and site-specific temperature responses (Fig. 2 & 3). The spread of temperature responses is fairly high and some sites even show a warming. However, considering the overall temperature responses of all sites, each event caused cooling (Fig. 3). The overall strongest cooling can be detected for the 1641 event (median = -0.71°C) followed by the 1601 event (median = -0.63°C). Both events also show the strongest cooling in the following year. The most recent events of 1783 (median = -0.37°C) and 1816 (median = -0.23°C) caused least cooling and the following year even shows no extraordinary temperature deviations.

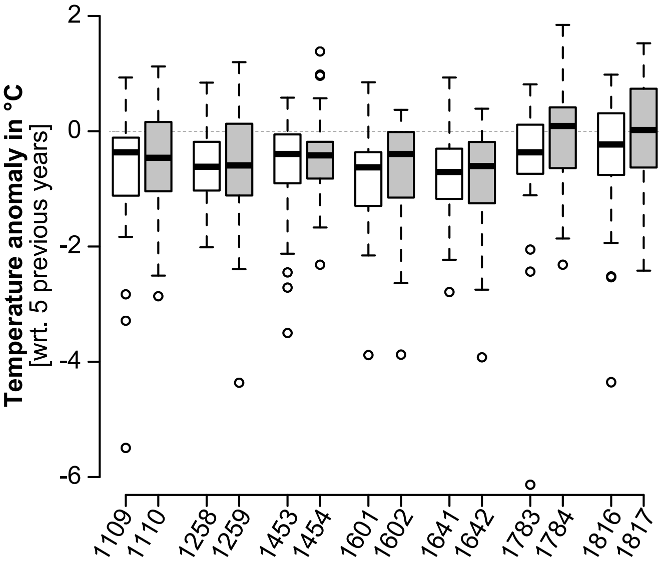

Figure 3: Comparison of the overall temperature response spread to seven major volcanic events.

Influence of geographical location

As mentioned above the temperature responses vary considerable among the sites but also among the events. However, by plotting the temperature anomalies with latitude we can partly determine a relationship with latitude (Fig. 4). Esper et al. (2015) found a more pronounced cooling in high compared to mid latitudes. This finding was derived from a superposed epoch analysis, i.e. represents the mean over a couple of events. By observing this pattern for single events this relationship is only partly true. A significant correlation between latitude and the strength of cooling can be determined for the 1453, 1601 and 1783 event as well as the post-event years 1259 and

1784. However, the slopes of the regression models are – albeit not significant – for the most part negative, indicating that cooling is frequently strongest with increasing latitude. This is most pronounced in 1453 with a temperature decrease of -0.36°C over 10° North as well as in 1783 with a cooling of -0.39°C with 10° North. However, in 1783 this slope is especially caused through the extraordinary strong cooling (-6.14°C) of a reconstruction site in Asia (Yamal).

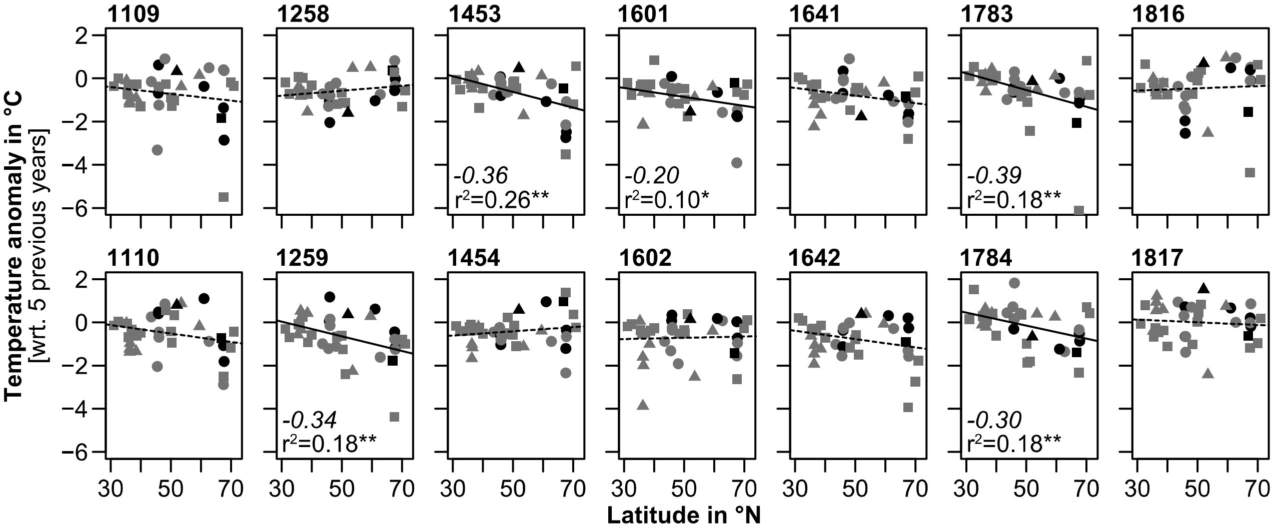

Figure 4: Temperature response in Europe (points), Asia (squares), and North America (triangles) to seven major volcanic events as a function of latitude. Upper panel shows temperature anomalies during the event year and lower panel for the respective following year (all wrt. to the 5 pre-event years). Grey symbols refer to TRW and black symbols to MXD based temperature reconstructions. Dashed lines represent non-significant and solid lines significant (p < 0.05, ** p < 0.01) linear fits. Italic values indicate the slope of the regression model over 10° North.*

Conclusion

Volcanically induced temperature responses can strongly vary in dependence to geographical location and differ among specific events. This is connected to the features of the volcanic eruption itself (location of the volcano, seasonal timing and strength of the eruption) but also to the atmospheric circulation patterns. In order to correctly represent volcanic forcing and the respective cooling in climate model simulations more research about the geographically varying cooling following different eruptions is needed. Ideally this has to be performed with MXD-based temperature reconstructions as MXD reflects more accurately the real temperature deviations than TRW (Anchukaitis et al. 2012, D'Arrigo et al. 2013, Esper et al. 2010, 2015). As only seven MXD-based reconstructions exist for the last millennium more effort has to be made for building up a denser millennium-length MXD-network. The site-specific temperature responses must be analysed in more detail to get a more accurate understanding of volcanically induced cooling.

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