Climate response to major volcanic eruptions

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It is a fundamental challenge to understand how much of the observed climate variability is a response to natural variations, as opposed to anthropogenic contributions or internal variability. Volcanic eruptions are one important cause of natural climate variations through radiative, chemical, dynamical and thermal perturbations in the climate system. Since major eruptions exert a strong short-term influence on climate, they are ideal to study the detection, isolation and attribution of a climate signal.

The climatic effect of volcanic eruptions is mainly due to injection into the lower stratosphere of large amounts of SO2, which are converted to sulphate aerosols. The tropospheric component is removed from the atmosphere within 1-3 weeks and has no significant long-term climatic effect. The stratospheric aerosols substantially perturb the Earth's radiative balance, causing warming and cooling at the same time. Increased absorption of radiation in the near-infrared results in a strong radiative heating in the lower stratosphere. On the other hand, strongly enhanced reflection of incoming solar radiation causes a global annual net cooling at the surface for typically 1-3 years (see Fig. 1).

The response of the climate system shows large hemispherical-to-continental, as well as seasonal, differences. The hemispherical differences are to some extent related to the latitudinal dispersal of volcanic aerosols into each hemisphere. The latitudinal transport is slower than the zonal dispersal and asymmetrical as a function of time of the year, location of the intertropical convergence zone (ITCZ) and the quasi-biennial oscillation (QBO).

The seasonal differences of the climate response are largest at the continental scale following tropical eruptions. Over northern hemispheric (NH) land regions, radiative cooling is dominant only in the summer half-year. During boreal winters, dynamical effects prevail, associated with anomalously warm conditions. GCM studies have shown that volcanic aerosols, which heat the tropical lower stratosphere through absorption, enhance the meridional stratospheric temperature gradient, which results in a strengthened polar vortex (Robock, 2000, and references therein). Stenchikov (2002) suggested an additional effect in the troposphere: Reduced solar radiation causes cooler tropospheric temperatures in the subtropics, which decreases the meridional tropospheric temperature gradient. This results in a reduction in the amplitude of planetary waves and allows the further strengthening of the polar vortex. Both processes force a positive phase of the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) causing winter warming over the NH land masses through enhanced advection of mild maritime air.

The volcanic signal is robust only on relatively large spatial scales and could easily be contaminated or completely obscured by other forcings or climate variability (e.g. strong ENSO events). Therefore, not every eruption is expected to cause a strong, immediate cooling (warming) but rather to bias the probability of occurrence of cold (warm) anomalies in post-eruption summers (winters). We visualise this shift in probability by analysing the volcanic signal in a European land temperature reconstruction by Luterbacher et al. (2004) going back to AD 1500. Figure 2 shows temperature anomalies for the summer (JJA, blue lines) and winter (DJF, red lines) in year 1 following 16 major tropical eruptions with respect to a 5-year pre-eruption period (see Fischer et al., 2006 for details). The black lines depict the corresponding anomalies in non-volcanic periods together with a fitted Gaussian distribution. A clear tendency to colder (warmer) conditions can be observed in post-eruption summers (winters). All 16 post-eruption summer episodes show a cooling (mean -0.48°C). Winter warming is not observed in all the cases but there is a clear shift (mean warming +0.73°C) in the probability of anomalous conditions (Fischer et al., 2006). Analysis of independent NAO index reconstructions reveal that the winter warming has often been associated with a positive phase of the NAO (not shown). A similar, yet less-pronounced, temperature signal is found in year 0, both in the summer and winter immediately following the eruptions.

In contrast to tropical eruptions, aerosols from mid and high-latitudinal eruptions often remain in the hemisphere into which they were injected. Hence, in these cases, the above-mentioned dynamical effect does not apply and radiative effects, which produce cooling, are dominant in winters following non-tropical eruptions (Oman et al., 2005). The two major high-latitudinal eruptions, Laki 1783 and Katmai/Novarupta 1912, were followed by anomalously cold NH winters.

Uncertainties and open questions

The findings presented above originate either from studies using instrumental data and multiproxy reconstructions or from climate model studies. Both approaches offer different potential but involve uncertainties and limitations, some of which will be highlighted in this section.

Volcanic record

A prerequisite to studying the impact of volcanic eruptions on climate is an exact record of the date, magnitude and location of eruptions. Most volcanic indices, such as the dust veil index (DVI) and the volcanic explosivity index (VEI), have limitations for use in climate studies. In recent years, Robertson et al. (2001) and Ammann et al. (2003) defined forcing data sets, based on sulphate records in ice-cores, which include estimates of the latitudinal distribution of volcanic aerosols. It is desirable that these promising approaches are supplemented with new high-resolution ice-core data from Greenland and Antarctica, as well as from glaciers in the mid- and low-latitudes, in order to account for the noise in the individual cores and to improve the representation of latitudinal aerosol dispersion. Furthermore, it is important to monitor the dispersion of aerosols from future eruptions by satellite and ground-based observations. Robock (2004) proposed the development of a data assimilation system using atmospheric models to produce a stratospheric aerosol data set out of the diversity of observations.

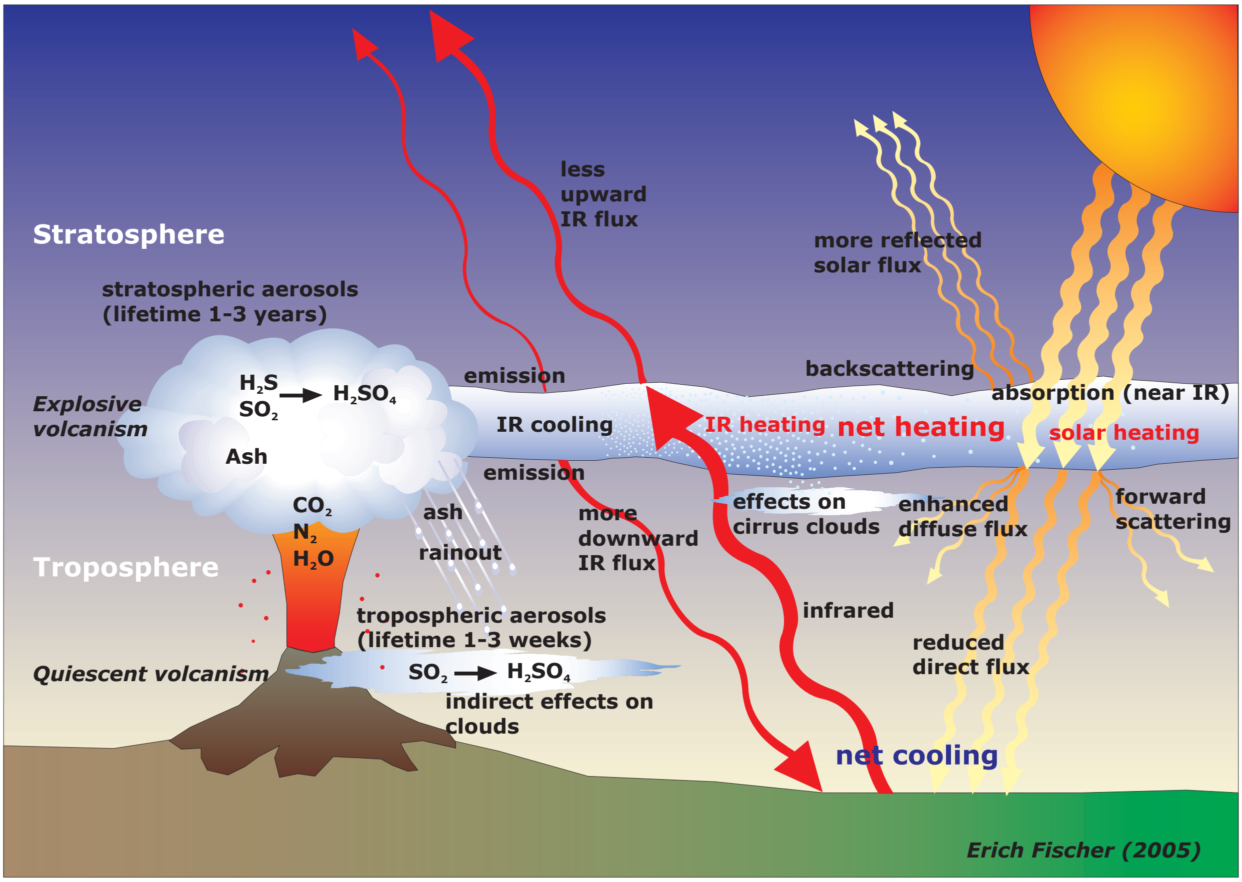

Figure 1: Schematic diagram of the impact of quiescent and explosive volcanism on the Earth's radiative balance. Redrawn after Robock (2000).

Observational and multi-proxy studies

Most studies using reconstructions or observations to determine volcanic influence are based on a single event or a set of a few events. Different post-eruption periods are often superposed to isolate the volcanic signals by averaging out non-volcanic variations. This method applies well to relatively large sets of eruptions. This implies long climate time series, as the frequency of major eruptions was relatively small in the past. Additionally, a good representation of interannual variability and seasonal resolution of the climate time series is required to account for the different effects in summer and winter. Recent high-resolution multi-proxy reconstructions allow detailed analysis of regional differences of the volcanic impact on climate (Luterbacher et al., 2004, Xoplaki et al., 2005). Care should be taken when deriving the temperature response directly from tree rings, since diffuse radiation may obscure the signal (Robock 2005).

Climate model studies

Additional benefit from an improved volcanic record could be derived for use in climate models. There are two main approaches to representing volcanic impacts in models. In some models, the volcanic influence is simply represented by a reduction of the effective solar constant. Annual global-to-zonal estimates of aerosol optical depth, derived from ice-cores, are translated to short-wave radiative forcing. With this method, the potentially important regional and timing information is not communicated to the model. Furthermore, dynamical effects through stratospheric warming and chemical effects cannot be simulated. Despite all the limitations, these models are still found to realistically simulate large-scale direct radiative volcanic effects.

Other models include a more sophisticated representation of volcanic aerosols in the form of stratospheric chemistry models. Time-height specification of the latitudinal aerosol concentrations and properties are imposed on the climate model. These models allow the analysis of the indirect effect of volcanic emissions on cirrus clouds (e.g. Lohmann et al., 2003). Robock (2004) formulates the ultimate goal as being the coupling of conduit models of magma, plume models and microphysical and transport models in the stratosphere to climate models, to predict the impact of the next large eruption as soon as it occurs.

There are still many processes in the climate response to past volcanic eruptions to be understood in more detail. For instance, the volcanic effects on precipitation are poorly known. Furthermore, it will be a challenge to predict the climate response to volcanic eruptions in a future climate with increased greenhouse and changing stratospheric ozone concentration. The key to a better understanding is a combination of model and observational studies, together with detailed monitoring of future volcanic eruptions.

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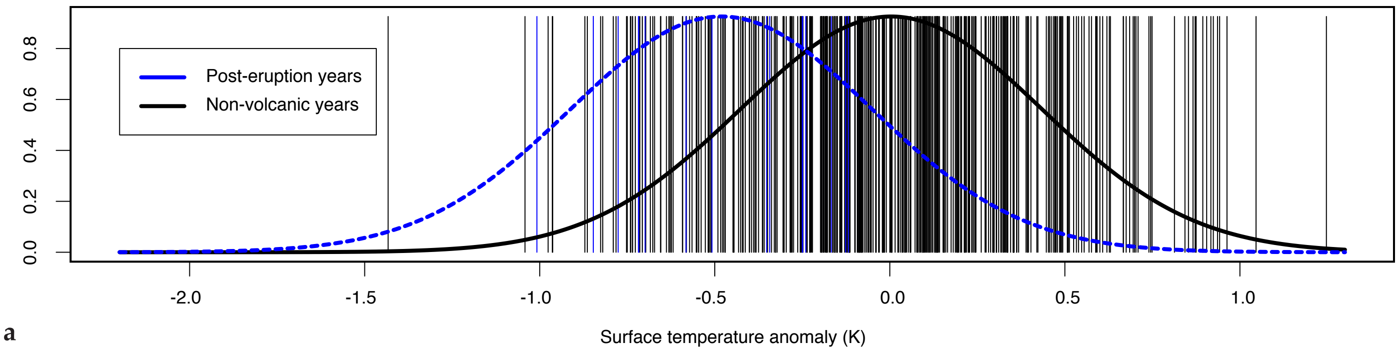

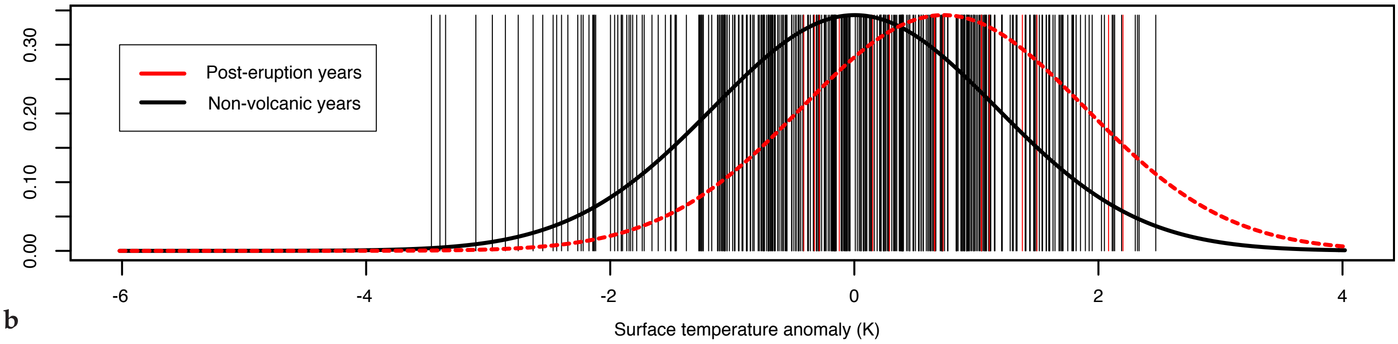

Figure 2: Temperature anomalies in the summer (JJA, blue vertical lines, Fig. 2a) and winter (DJF, red vertical lines, Fig. 2b) in year 1 following 16 major tropical eruptions over the last 500 years with respect to a 5-year pre-eruption period. Black vertical lines depict the corresponding anomalies in non-volcanic periods. Temperature reconstructions by Luterbacher et al. (2004) are averaged over European land regions (25°W-40°E, 35°N-70°N) and cover the past half-millennium. The Gaussian distribution fitted to the non-volcanic seasons is indicated in black. Blue (red) dashed lines visualise the same distribution shifted by the mean anomaly in the post-eruption summer (winter). Note that the absolute temperature departure in summer is somewhat weaker than in winter. However, the substantially larger winter temperature variability has to be taken into account. Since the small number of volcanic events allows no statement on the variability in post-eruption seasons, we assume no change in the standard deviations.

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