

Toward predicting volcanically-forced decadal climate variability

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Volcanic forcing and climate

Strong volcanic eruptions inject into the stratosphere massive amounts of chemically and microphysically active gases that lead to the formation of aerosol particles, affecting the Earth's radiative balance and climate (Robock, 2000; Timmreck, 2012; LeGrande et al., 2016). Sulfate aerosol particles scatter solar radiation back to space, which results in global surface cooling and slowdown of the global hydrological cycle. The particles also absorb radiation in the infrared and near-infrared bands, causing local warming of the lower stratosphere. Both direct radiative forcing effects are temporary, their time scale being set by the persistence of the volcanic aerosol cloud in the lower stratosphere. This amounts to a couple of years in the case of the strongest recent tropical eruptions, such as the 1815 eruption of Mt Tambora in Indonesia (Fig. 1a). However, the climatic impact of strong volcanic eruptions can last well beyond the timescale of the direct radiative perturbation through the dynamic alterations it induces in the entire coupled climate system. These include "feedbacks" in their classic definition of amplification and dampening loops related to changes in climatic variables that operate through changes in global-mean surface temperature (Boucher et al., 2013). For instance, the so-called "polar amplification" of climate signals – mainly a consequence of positive feedbacks involving snow cover and sea ice – provides one element of inter-hemispheric asymmetry to the decadal climate response to volcanic eruptions through global radiative cooling (Zanchettin et al., 2014). Dynamical impacts further stem from the spatially heterogeneous structure of volcanic forcing. In the case

of tropical eruptions, for which the bulk of the volcanic aerosol cloud remains largely constrained in the tropical stratosphere, simple theoretical arguments indicate that the aerosol radiative heating enhances the upper-level equator-to-pole temperature gradients that, by thermal wind balance, can force a strengthened stratospheric polar vortex in both hemispheres, as diagnosed from climate models (e.g., Stenchikov et al., 2002; Zanchettin et al., 2014). The consequent downward penetration of the westerly wind anomalies at the edge of the polar vortex and their interaction with topography provide further elements of a top-down atmospheric mechanism of volcanic forcing. In the Northern Hemisphere, its tropospheric effects during the first post-eruption winter typically project on a positive anomaly of the North Atlantic Oscillation/Arctic Oscillation (NAO/AO) and associated continental warming (Stenchikov et al., 2006; Graf et al., 2014; Zambri and Robock, 2016). This is a key component of a major recognized general pathway of volcanically-forced decadal climate signals (Otterå et al., 2010; Zanchettin et al., 2012).

Specifically, the NAO-related post-eruption modifications to the wind field modify the circulation in the upper North Atlantic Ocean and locally enhance oceanic convective mixing through anomalous turbulent heat and freshwater fluxes. These superpose on the extensive buoyancy effects of the post-eruption radiative cooling, leading to strengthened deep water formation. The slow propagation of so-formed water masses in the ocean abyss is expected to protract the fast oceanic response

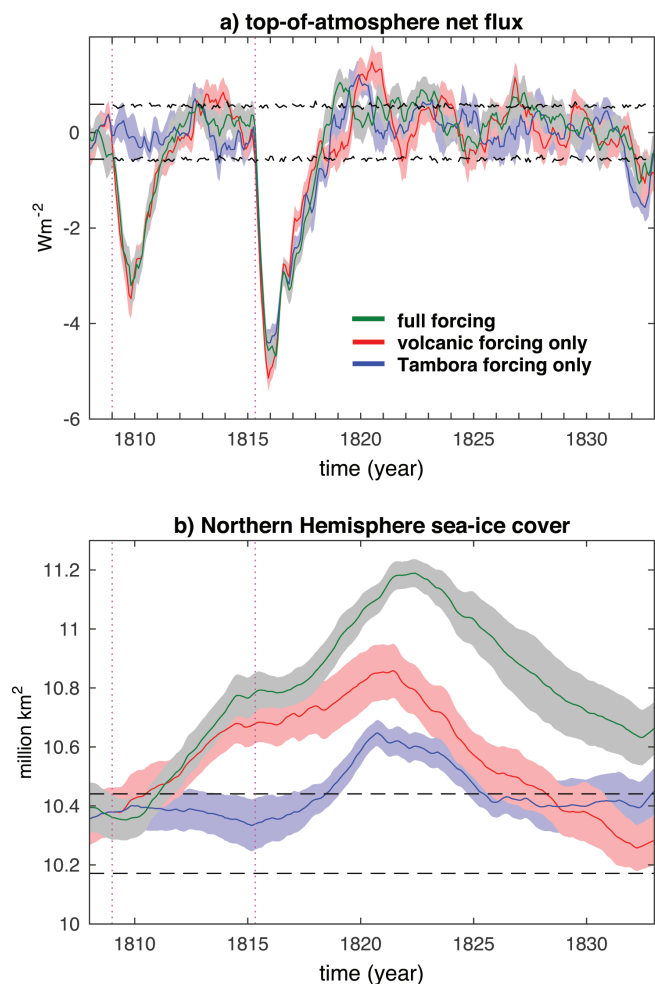


Figure 1: Simulated global-average top-of-atmosphere net radiative anomalies (a: 3-month smoothing) and simulated Arctic sea ice cover evolution (b: 61-month smoothing) around the 1815 Tambora eruption in three climate simulation ensembles with the ECHAM5/MPIOM coupled climate model, differing in the ensemble-mean initial state and in the applied forcing. Dark green: full-forcing conditions (including the Dalton Minimum of solar activity); Red: volcanic forcing-only conditions, including both the 1809 and 1815 eruptions; Blue: volcanic forcing-only conditions, without the 1809 eruption. Lines (shading): mean ($1\text{-}\sigma$ standard error of the mean). Black dashed lines: 5^{th} – 95^{th} percentile intervals for signal occurrence in the control run. Vertical dotted lines indicate the 1809 and Tambora eruptions. Each ensemble consists of 10 simulations differing in the initial state. Note that the Arctic sea ice response is significantly different in the three ensembles whereas the applied forcing, in terms of anomalous top-of-atmosphere net flux, is practically indistinguishable. For details see: Zanchettin et al. (2013a).

to decadal time scales through the tendency for reinvigoration of the oceanic meridional overturning circulation that culminates several years – up to a decade or so – after major eruptions, as diagnosed from models. Implications for meridional ocean heat transports and sea ice dynamics contribute to regional characterization of the signal, and hence to recognizable traces of volcanic signals especially in extratropical and polar regional

climates (Zanchettin et al., 2012, 2013b; Sicre et al., 2013). Lacking further external excitation (e.g., by a successive eruption), negative feedbacks eventually become predominant and the near-surface system relaxes back to the mean pre-eruption state as part of a roughly bi-decadal fluctuation. The feedback loop thus sets the phase of internal modes of interdecadal climate variability (Otterå et al., 2010), whose effects can be protracted, with dampening intensity, beyond one fluctuation (Swingedouw et al., 2015). In the latter case, deep ocean anomalies may remain significant for much longer (Gleckler et al., 2006; Gregory, 2010). A similar interdecadal general oceanic response is also found for high-latitude eruptions, for which it is the direct radiative surface cooling at subpolar latitudes linked to the confinement of the volcanic aerosol cloud to the eruption’s hemisphere that typically leads to enhanced oceanic deep convection (Fig. 2, see also Pausata et al., 2015).

Knowledge gaps

The general framework outlined above is useful to identify the core dynamics involved in post-eruption decadal climate variability. However, several caveats must be taken into consideration. Above of all, direct observations of strong volcanic eruptions are very few – only five in the instrumental period – which does not allow robust statistics of their climate impact, and hence attribution. Therefore, large part of our knowledge builds on climate model simulations and proxy-based climate reconstructions, both of which have large uncertainties and deficiencies (e.g., Zanchettin, 2017). Incessant improvement in both tools brings old evidence back into the discussion. For instance, the mechanisms leading to a preferred enhanced stratospheric polar vortex in post-eruption winters have been questioned by recent studies suggesting that the mechanism based on the thermal wind balance and outlined above does not always hold (e.g., Bittner et al., 2016), possibly as the zonal wind response to direct aerosol radiative heating may be dominated by other effects, such as the residual circulation response to anomalous wave activity (Toohey et al., 2014). Accordingly, obvious implications for the polar vortex response stem from the tropical Pacific, a known critical source of tropospheric wave disturbances affecting stratospheric dynamics (e.g., Graf et al., 2014). Instrumental observations and climate proxy-based reconstructions indicate that volcanic eruptions tend to be followed by an El Niño event. A newly discovered causal mechanism is initiated by cooling over Africa (the largest tropical landmass), which reduces precipitation and forces an atmospheric Kelvin wave response that couples with western Pacific convection to trigger westerly wind anomalies and a Pacific El Niño. While modulated by the seasonal cycle of convection, the effect of volcanism onwind forcing over the Pacific persists during the year after the eruption, implying that the Pacific El Niño-like response involves more external forcing than traditional,

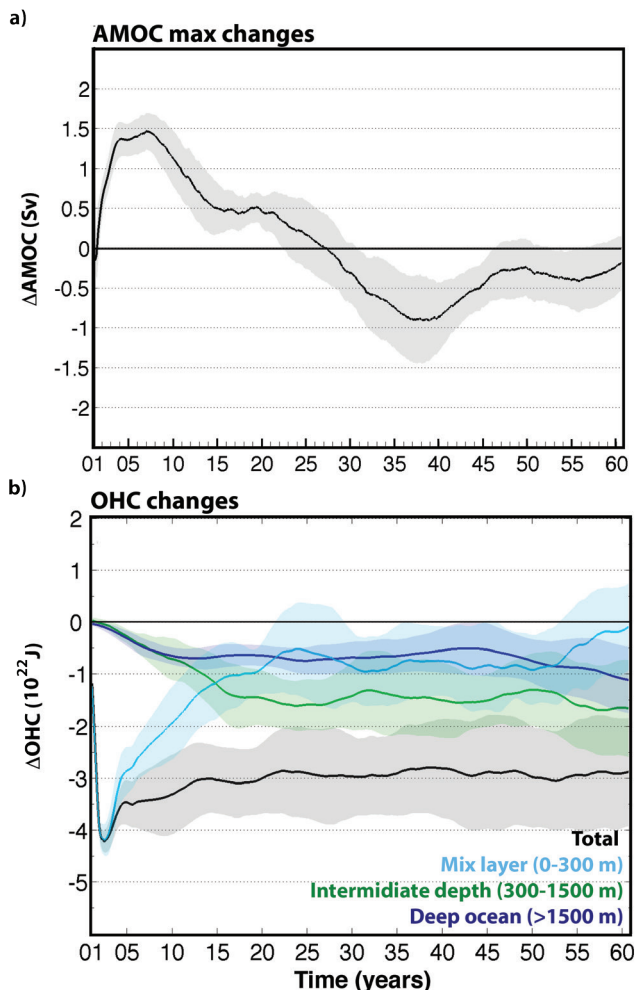


Figure 2: Decadal oceanic response to a high-latitude eruption resembling the multistage 1783 eruption of Laki (Iceland) simulate by the NorESM coupled climate model. a) Changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) estimated as the maximum of the zonally-integrated overturning stream function in the Atlantic. b) Changes in Ocean Heat Content (OHC) averaged from the surface to selected depths for the global ocean. In both panels the solid lines denote the ensemble average changes and shadings represent the confidence intervals at approximate 95% level (twice the standard error of the mean) of the difference in all pairs of experiments that comprise the ensembles. The ensemble consists of 10 simulations differing for the initial state. Anomalies are calculated with respect to a control simulation. The figure has been adapted from Pausata et al. (2015).

internally generated events (Khodri et al., 2017). However, there are stratospheric (e.g., Scaife et al., 2009) and tropospheric (e.g., Graf and Zanchettin, 2012) pathways of El Niño forcing on the atmospheric circulation over the North Atlantic that project on a negative NAO; this would counteract the NAO+ tendency above described. In addition, sampling issues in simulation ensembles (Lehner et al., 2016) and uncertainty linked to the eruption’s season (Stevenson et al., 2017) are recently proposed explanations for reconstructions-simulations

discrepancies in the estimated post-eruption cooling. This outlines the complexity of competing influences on the top-down mechanism of volcanic forcing, hence on the post-eruption positive NAO anomaly for moderate or small tropical eruptions, whose uncertainty cascades on the decadal oceanic response. Ocean dynamics simulated by coupled models are another major source of uncertainty to be understood considering the different time scales of simulated oceanic responses (Otterå et al., 2010; Mignot et al., 2011; Zanchettin et al., 2012). Furthermore, the fact that a climate model spontaneously generates bi-decadal variability in the overturning circulation strength seems to determine its excitability to the general response mechanism outlined above (Swingedouw et al., 2015).

Inherent sources of uncertainty

The climatic response to a given volcanic eruption is highly specific. First, the general response mechanism strongly depends on the characteristics of the forcing. An obvious determinant factor is the magnitude of the eruption, whose potential control can be, for instance, estimated looking at the sea ice response. For a very strong eruption, polar amplification of the global cooling signal may lead sea ice to cover regions of strong oceanic deep convection, thereby hampering deep water formation through insulation of the ocean-atmosphere boundary. Associated increased freshwater export from the Arctic also contributes to stabilize the ocean water column. These will lead ultimately to a tendency for weakening – instead of strengthening – of the thermohaline circulation (e.g., Zhong et al., 2010; Mignot et al., 2011). Second, the way the volcanic aerosol cloud distributes in the stratosphere influences both the direct radiative and dynamic atmospheric responses (e.g., Toohy et al., 2014; Colose et al., 2016). In this regard, the latitudinal position of the erupting volcano is an obvious determinant factor, but similar uncertainty on the spatial structure of the volcanic aerosol cloud can be originated by the season of the eruption (Stevenson et al., 2017).

A milestone in our understanding of volcanically forced decadal climate variability was the recent recognition that the mean climate state, the phase and amplitude of ongoing internal variability at the time of an eruption, such as that associated with major climatic modes including, e.g., El Niño Southern Oscillation (ENSO) or the Quasi-Biennial Oscillation (QBO), and the presence of additional forcing factors crucially determine how the climate system responds to the volcanic forcing (Zhong et al., 2010; Zanchettin et al., 2012, 2013a; Berdahl and Robock, 2013; Swingedouw et al., 2015; Pausata et al., 2016). Fig. 1 (after Zanchettin et al., 2013a) shows the role of background conditions for the case of Arctic sea ice response to the 1815 Tambora eruption simulated in three ensembles in which the volcanic forcing is the same but background climate state and histories are different. Results show that a significant increase in Arctic sea

ice cover is consistently diagnosed after the eruption in all ensembles but the average anomalies differ in both magnitude and duration. The inter-ensemble differences in the Arctic sea ice response reflect substantial differences in the decadal feedback mechanisms activated in the coupled atmosphere-ocean-sea-ice system after the eruption.

This dependency on the background climate state can partly explain the different, often contrasting, results found for simulated and reconstructed post-eruption decadal variability from different volcanic eruptions (Zanchettin et al., 2013a,b). This concept also allows understanding how the timing between subsequent volcanic eruptions can deterministically influence the response in the case of a volcanic cluster. Specifically, if two eruptions are roughly paced at one period of the above-mentioned decadal mechanism (roughly two decades), they will interfere constructively, as they will occur around the same phase of internal modes of oceanic variability. In contrast, if they are paced at half the period of the mechanism (a decade or so), they will interfere destructively (Swingedouw et al., 2015). Intriguingly, both cases apply to the most recent strong volcanic eruptions: Agung in 1963 and El Chichón in 1982 are paced at roughly two decades (constructive interference), while El Chichón and Pinatubo in 1991 were paced at roughly one decade (destructive interference). This finding widens margins for long-term predictability of decadal climate impacts by strong volcanic eruptions.

Opportunities for progress

A series of research initiatives are currently contributing to building the scientific basis for reaching such an ambitious objective by filling major gaps of understanding. A first goal of current research is robust characterization, by means of climate models with interactive stratospheric aerosols, of the forcing generated by a given eruption based on the estimated amount of gaseous sulphur species it injects in the stratosphere. The WCRP/SPARC Stratospheric Sulfur and its Role in Climate (SSiRC) initiative (<http://sparc-ssirc.org/ssirc.html>, Timmreck et al., 2016b) coordinates the international activities on stratospheric aerosol research aiming at better understanding and hence modeling of the stratospheric aerosol layers and their controls. SSiRC will help study why the characterization of the volcanic aerosol cloud and the radiative forcing generated by state-of-the-art global aerosol models for a certain sulphur injection remain highly uncertain (e.g., SPARC, 2006; Zanchettin et al., 2016). Focus will be in particular on model inconsistencies related to the treatment of aerosol microphysics and climate physical processes, such as stratospheric circulation and stratosphere-troposphere coupling.

In addition, unpredictability of timing and magnitude of volcanic eruptions is a major source of uncertainty and the climate community should be prepared for such

an eventuality. Therefore, a new SSiRC initiative called VolRes ("Volcano Response Plan after the next major eruption") has been launched aiming at developing a scientific plan to prepare observational and modelling tools and strategies to be readily applied for the next major volcanic eruption. Characterization of the potential climatic impact of an eruption in the more distant future (such as envisaged for end-of-the-century warming scenarios) bears additional uncertainties related to the dependence of dynamics of the eruption plume on the atmospheric stratification and tropopause height, in turn subject to global temperature changes (Aubry et al., 2016).

Finally, the "Model Intercomparison Project on the climatic response to Volcanic forcing" (VolMIP) (Zanchettin et al., 2016) has been created as part of the Coupled Model Intercomparison Project phase 6 (CMIP6), to define a coordinated protocol for idealized volcanic-perturbation experiments to improve comparability of results across different climate models. Interest is on various aspects of volcanically-forced climate variability, with specific sets of experiments designed to investigate both the seasonal-to-interannual atmospheric response and the interannual-to-decadal response of the coupled ocean-atmosphere-sea-ice system. Through systematic and consistent (across the different models) sampling of internal variability (e.g., ENSO, QBO), VolMIP will allow the identification of robust response mechanisms to volcanic forcing or explain the lack thereof.

VolMIP will also foster investigation of simulated Southern Hemispheric responses to volcanic forcing, currently an overlooked topic due to the known severe climate model biases in the Southern Hemisphere (e.g., Simpson et al., 2012; Salleé et al., 2013; Turner et al., 2013). More generally, if volcanically-forced decadal climate variability can be understood through the excitation by volcanic forcing of internal modes of climate variability, confidence must be built on the accurate and robust simulation of such modes. Current climate models, however, have difficulties in reproducing the observed spatial pattern, time scales and teleconnections of dominant modes such as ENSO (e.g., Zou et al., 2014) or the Atlantic Multidecadal Oscillation (Kavvada et al., 2013).

Only a few studies specifically focused on the quantitative assessment of volcanic forcing impacts on decadal climate predictions and potential predictability (Collins, 2003; Shiogama et al., 2010; Timmreck et al., 2016a). Overall, in the presence of strong natural climate variability on the one hand and because of different magnitude and frequency of volcanic eruptions on the other hand, it is difficult to assess the potential predictability from volcanoes of regional climates. Improvements of decadal climate prediction systems concerning implementation of volcanic forcing (e.g., LeGrande et al., 2016) and bias estimation and correction (e.g., Hawkins et al., 2014) are milestones toward robust prediction of volcanically-

forced decadal climate variability. Along this long-term goal, within CMIP6, a joint decadal climate prediction experiment between VolMIP and the Decadal Climate Prediction Panel (Boer et al., 2016) will be conducted to address the climatic implications if a Pinatubo-like eruption would have occurred in 2015.

In conclusion, there is emerging evidence that volcanic forcing can significantly affect decadal climate variability through mechanisms that are increasingly better understood. Milestones on the road toward robust prediction of volcanically-forced decadal variability include improved understanding and implementation of aerosol forcing in decadal prediction systems and improved simulated representation and estimation of internal decadal climate variability.

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